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AIR VEHICLE INTEGRATION AND TECHNOLOGY RESEARCH (AVIATR)

Task Order 0003: Condition-Based Maintenance Plus Structural Integrity (CBM+SI) Demonstration (September 2011 to March 2012)

Keith Halbert, LeRoy Fitzwater, Tony Torng, Paul Kesler, and Harry Millwater

The Boeing Company

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Interim Report

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14. ABSTRACT

This report summarizes progress made on the AVIATR contract, Task Order 0003, Condition-Based Maintenance Plus Structural Integrity – Option Phase during the reporting period September 2011 through March 2012.

The updated CBM+SI process flowchart is presented, which represents an overview of the work being performed on this project. The remaining sections discuss topics within the flowchart that have been tasked during the reporting period.

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1. Platform Level (Option Phase) Introduction

This report summarizes recent progress made on the AVIATR contract Task Order 3, Condition Based Maintenance plus Structural Integrity (CBM+SI) – Option Phase. Similar to previous progress reports during the Option Phase, the report in general follows the process detailed in the flowchart shown in Figure 1. A detailed general purpose flow chart is presented in Section 2. This is followed by a detailed application for the general process to our specific application on the F-15 wing demonstration in Section 3. The remaining sections tackle specific topics within the flowchart that have been tasked during the reporting period. In this progress report tasks related to in-situ sensor system capability analysis (Section 4), updates to the component level risk analysis (Section 0) and cost benefit analysis (Section 6) are discussed.

The discussion on “in-situ sensor system capability analysis” looks to address how the normal aging of the system will impact the risk assessment and to define a set of requirements on the system to provide a minimum level of quality information that will not have gross negative impact on the risk analysis in the timing of inspections and maintaining structural integrity. In Section 5, a number of changes have been made, e.g., increasing the number of control points (CPs) utilized in the analysis, an automated process has been implemented to determine the optimal inspection strategy, and a more exhaustive collection of strategies is considered for each CP, as well as other refinements discussed in the section. Similarly, in Section 6, which discusses changes in the cost-benefit analysis some of the changes and updates include, an expanded worksheet capability which can now handle up to 50 CPs, the worksheet has been made more computationally efficient, as well as reorganized to make it more accessible. It has been updated to provide a scheme for determining the optimal Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM) inspection strategies for each CP, and the system level cost-benefit analysis.

Very nearly all of the basic component based risk analyses are complete at this point. While there is still opportunity for refinement, the basic architecture across various types of CPs is complete. The team is continuing to refine the basic approach to remove conservatism that plagues some CPs with exceptionally high risk estimate. At this point the focus will shift to documenting the sources of uncertainty in the basic component risk analysis, and considering the system level risk analysis both at the local level where a specific CP may have multiple crack initiation sites (i.e. bolt holes). To date, we have considered each bolt hole for an individual CP independent and equally likely to initiate and precipitate crack growth. This is not strictly correct, and the approach is to develop a system level like analysis to more accurately estimate the risk estimate at the individual CP level. Also, the more traditional system risk analysis considers the suite of CPs to estimate the reliability of the wing as an entire system, at least, at the level of the wing structural reliability being exclusively defined by the collection of CPs. Other areas for future development are integration of higher fidelity loads, correlation of risk estimates with observations from the field, and, returning to the high risk CPs, assessing the fidelity of stress intensity factors and fracture toughness distributions used in the initial deterministic analysis.

2. CBM+SI Process Flowchart

2.1. Introduction

The CBM+SI Process Flowchart in Figure 1 is a deliverable of this work. The goal is to create a flowchart which can be used to generate an optimal condition-based maintenance plan for a structural system which maintains structural integrity. The flowchart incorporates the use of maintenance technology which may include repair methods, NDE, SHM, in-situ sensors, corrosion sensors, or many other technologies of similar scope.

To facilitate the development of this flowchart the team is performing an in-depth structural risk assessment of the F-15 fighter wing, considering crack growth as the failure mechanism. While this specific project is helping to clarify the required tasks for CBM+SI, the team is attempting to maintain generality where feasible.

Note that the flowchart is a work in progress. As we move forward to more complex aspects of the F-15 wing analysis, changes to the flowchart may be made. In addition, it is the intention of the team to produce detail flowcharts that are specific to the in-situ sensor capability analysis, risk analysis, and cost-benefit analysis sections of this report. However, these are still in work.

In this section of the report the high level flowchart is shown and explained in general terms. In Section 3, the flowchart is applied to our specific problem at a relatively high level. This will facilitate the communication of the use of the flowchart, as well as give a current overview of the CBM+SI project. In later sections each major component of the analysis (in-situ sensor capability analysis, risk analysis, cost benefit analysis) is extensively detailed.

2.2. Flow Chart Components

Each component of the flowchart in Figure 1 is briefly explained in this section. The application is described in general terms. Specifics pertaining to the F-15 wing analysis are included in later sections of this report.

2.2.1. Establish Analysis Framework

The foundational assumptions are put in place here, such as: the Technical Performance Measures (TPMs), failure mechanism, safety criterion, etc.

2.2.2. Acquire Structural System Information

Data pertaining to the structure of the fleet in question must be obtained. For example, the fleet size, service life, average hours per flight, spectrum, etc.

2.2.3. Acquire Control Point Information

Part-specific information regarding the structural details under consideration must be obtained: material, geometry, maintenance history, damage tolerance analysis, etc.

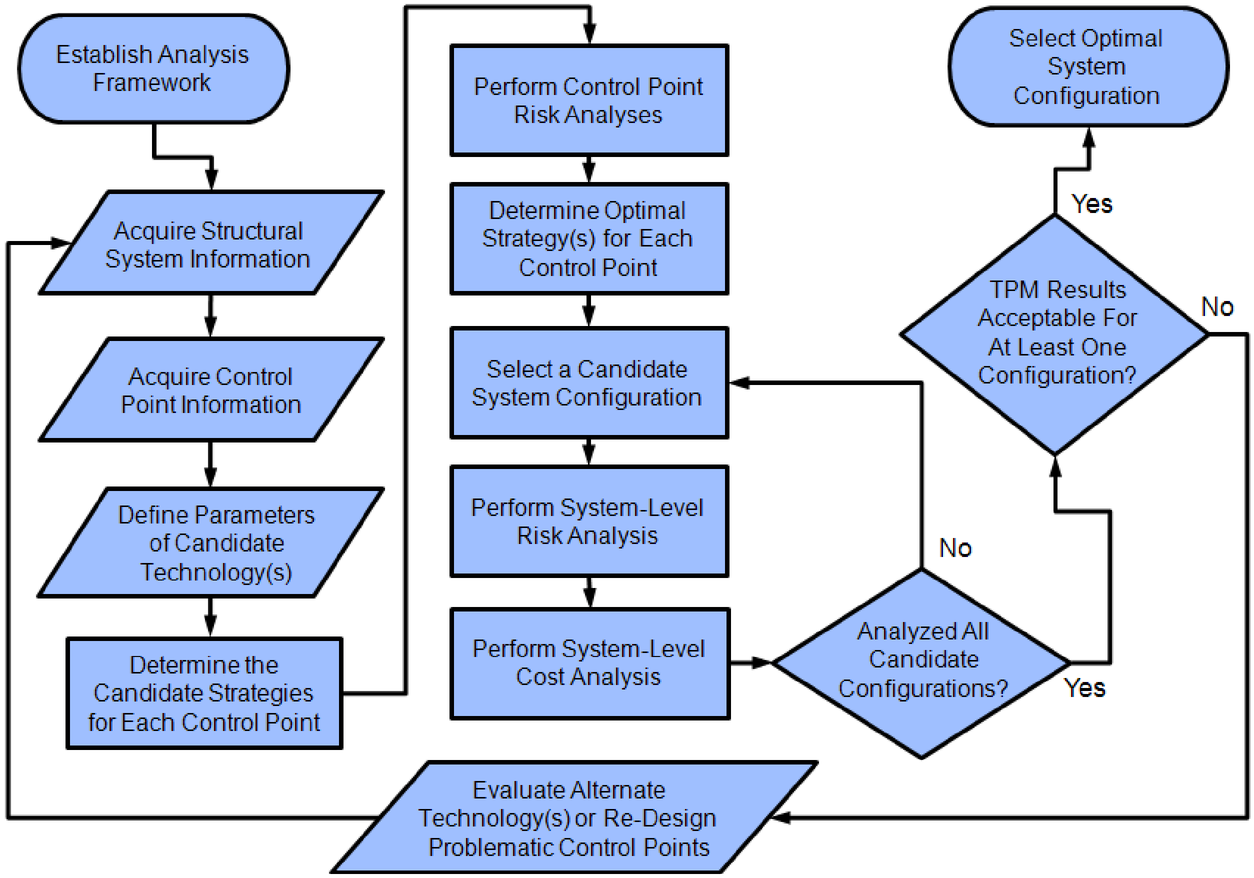

Figure 1. CBM+SI High-Level Process Flowchart

2.2.4. Define Parameters of Candidate Technology(s)

The particulars of the technology(s) being considered which pertain to the analysis at hand must be carefully described. For example, the detection capability of a damage sensing technology, the quantified ability of a repair method to restore structural integrity, the anticipated development and maintenance costs of the technology, etc.

2.2.5. Determine the Candidate Strategies for Each Control Point

A *strategy* for a CP consists of the complete maintenance plan for the structure for the duration of the service life. For example, this may include: NDE inspection every three years, reaming out of fastener hole for a small flaw, and replacement of the part in the event of a large flaw. Another competing strategy may call for inspections every two years or a novel large flaw repair method.

2.2.6. Perform Control Point Risk Analyses

For each candidate strategy identified in the previous step for each CP, the risk analysis must be performed to assess the structural risk over the service life. Of course, the particulars of the risk analysis depend on the damage mechanism, type of structure, and many other factors. These component-level analyses are performed prior to the system-level

analysis because it is beneficial from a practical standpoint to identify those strategies which can be discarded before embarking on the relatively complex system-level analysis. At this point it may be possible to discard certain strategies which have been shown to be incapable of maintaining safety according to the risk requirements set forth in the preliminary step “Establish Analysis Parameters”.

2.2.7. Determine Optimal Strategy(s) for Each Control Point

This step is closely related to the previous step. With the CP risk analyses in hand, preliminary cost estimates can be made to determine which strategies should remain under consideration. Again the goal is to discard infeasible or cost ineffective strategies because the system-level analysis is exponentially more complex than the component-level analysis.

2.2.8. Select a Candidate System Configuration

A *configuration* refers to a single collection of strategies, one for each CP in the model. The singular tense of the title of this step is intended to imply that, due to the complexity of the system-level analysis, one configuration should be considered at a time. The first iteration of the system-level analysis is conducted using each optimal strategy for each CP. Note that an exhaustive list of possible configurations may be exceedingly long. For example, a system of 20 CPs, with 2 optimal strategies for each CP, has 2^{20} (over one million) possible configurations. This should highlight the importance of carefully identifying those strategies for each CP which are indeed optimal as every additional strategy included for a CP *doubles* the total number of configurations in the exhaustive list.

Note that this step, along with the following two steps, represents a single iteration of the analysis of a configuration. In a given analysis it may be beneficial to automate these three steps such that the list of potential configurations can be analyzed as a batch.

2.2.9. Perform System-Level Risk Analysis

For the current configuration under consideration, the system-level risk analysis is performed. Again, the particulars of the risk analysis depend on the specific problem under consideration and must be examined thoroughly on a case-by-case basis. The bulk of the work will likely be in performing the first analysis for a single configuration, after which subsequent configurations can be mechanically run through the developed analysis process, with automation potentially being of high value due to the possibility of having a long list of configurations to evaluate.

2.2.10. Perform System-Level Cost Analysis

At this point the TPMs described in the preliminary step “Establish Analysis Framework” are calculated for the configuration of interest. This step may be very involved. The results of the system-level risk analysis will likely be used as an input here (to calculated the expected costs of repairs and failures over time), along with the costs associated with the maintenance technology(s) being evaluated. As in the system-level risk analysis, the bulk of the work will be performed in setting up the model for analyzing a single configuration. Once this is complete other configurations may be mechanically evaluated (with automation possibly beneficial).

2.2.11. Analyzed All Candidate Configurations?

When the process of calculating the TPMs has been completed for all configurations under consideration, we are ready to proceed to the decision making portion of the flowchart.

2.2.12. TPM Results Acceptable For At Least One Configuration?

Judgment may be required here to determine if the TPMs as calculated are acceptable for any of the configurations. If they are not (for example, if the baseline is clearly superior, or if no configuration meets the risk requirement) then we are required to move back to nearly the beginning of the flowchart. If at least one configuration is deemed acceptable, we may proceed.

2.2.13. Evaluate Alternate Technology(s) or Re-Design Problematic Control Points

In the event that no configuration has been deemed acceptable, the cause of this must be identified. It may simply be that the technology is not as effective as necessary. Or, there could be a small number of CPs which contribute a critical amount of risk to the system. A great deal of judgment is required at this stage and the process of identifying the optimal course of action may be highly dependent on the specific application.

2.2.14. Select Optimal System Configuration

From the list of acceptable configurations, that configuration which is optimal in terms of the various TPMs is identified and recommended. Note that several of the TPMs defined in “Establish Analysis Parameters” may be conflicting. Hence judgment may be required here to identify the optimal configuration.

3. Example Application of CBM+SI Process Flowchart

The structural system under consideration was detailed in the previous progress report. This is briefly reviewed here with minor updates.

Examination of the F-15's Force Structural Maintenance Plan (FSMP) and the Silver Bullet Risk Analysis report (Document LF08-084) had identified a total of 66 CPs of aircraft C/D for consideration. This list was trimmed for the following reasons:

- Nine (9) CPs removed due to lack of associated damage tolerance analysis
  - No DTA # associated
- Five (5) CPs removed due to risk analysis indicating that no inspections are required over the service life
  - 051B, 053A, 053B, 089D, 163
- Six (6) additional CPs removed due to indication of zero required inspections after the associated damage tolerance analysis was updated to include the effect of residuals stresses
  - 164, 165, 047, 050B, 052B, 089C
- One (1) CP removed due to insufficient data to conduct risk analysis
  - 167
- One (1) CP removed due to being unique and unusual (part cannot fail, repair only)
  - 142

At this time the analysis includes a total of 44 CPs. In Table 1, the collection of 44 CPs is shown along with some relevant information.

To better communicate the flowchart, the application of the steps are described in this section as they pertain to the probabilistic damage tolerance analysis of the F-15 C/D wing system. This high level view is not intended to be a complete picture of the status of the analysis. Rather, it is intended to translate the narrative of the process via example. Also, it is intended that this chapter could be read by someone who wishes to obtain familiarity with the scope of the project without getting into the technical details of the work. The core technical components of the CBM+SI project (SHM, risk, and cost analyses) are discussed in detail in separate sections of this document.

Note, some of the following is taken from the previous progress report. This is done to reduce the need to refer to the outdated document.

3.1. Example: Establish Analysis Framework

3.1.1. Identify the Task

The goal of this task is to identify an optimal maintenance plan for the F-15 wing structural system utilizing a combination of traditional NDE, an in-situ crack detection technology, and the existing repair methodologies for the structure. For a maintenance plan to be acceptable, the risk is required to adhere to the specifications of MIL-STD-1530C. Ultimately the potential maintenance plans are compared via the TPMs, which are related to the cost of ownership of the fleet and to aircraft availability.

Depot CP	Material	Sim Locs	Field CP	Material	Sim Locs
056	Al	32	054B	Al	6
059B	Al	74	054C	Al	6
097	Ti	2	055	Al	36
115	Al	95	057B	Al	32
124B	Al	12	063B	Al	32
126B	Al	40	112B	Al	88
131	Al	96	114	Al	40
133A	Al	60	116	Al	46
134B	Al	8	130B	Al	2
135B	Al	28	139	Al	116
137B	Al	8	140	Al	30
138B	Al	4	166B	Ti	2
141	Al	92	180	Al	236
143	Al	2	184	Al	48
144	Al	2	187	Al	134
145	Al	54	188	Al	20
179	Al	236	191	Al	6
181	Al	16	194	Al	22
182	Al	32			
183	Ti	78			
192	Al	12			
195	Al	46			
196	Al	6			
201	Al	32			
202	Al	18			
203	Al	2			

Table 1. Basic Information on 44 Control Points of F-15 C/D Wing System

3.1.2. Risk Requirement

Structural safety is characterized by the risk associated with each CP's Single Flight Probability of Failure (SFPOF). This term is the statistical representation of the likelihood of a CP to catastrophically fail during flight. MIL-STD-1530C documents the requirement by which the SFPOF must not exceed:

"A probability of catastrophic failure at or below 10^{-7} per flight for the aircraft structure is considered adequate to ensure safety for long-term military operations. Probabilities of catastrophic failure exceeding 10^{-5} per flight for the aircraft structure should be considered unacceptable. When the probability of failure is between these two limits, consideration should be given to mitigation of risk through inspection, repair, operational restrictions, modification, or replacement."

In the work to date the 10^{-7} threshold is applied to each CP individually, rather than to the system as a whole.

3.1.3. Technical Performance Measures (TPMs)

The cost of maintaining the fleet is summarized through the Net Present Value of expenditures (NPV), or the discounted costs. Thus, a lower NPV is preferable. Note that in finance in general the net present value represents profit and loss, however, in this analysis we are concerned only with costs. Rather than place a negative sign on every value, costs are shown as positive and the reader must keep that in mind. That is, when discussing costs, *lower is better*.

The Life Cycle Cost (LCC) is also occasionally used. LCC is similar to NPV but does not account for the time value of money.

The team has not yet determined exactly which measure of aircraft availability is most appropriate. In this document, the expected downtime for the fleet in hours due to maintenance of the wing system is reported because this measure has a straightforward interpretation. This TPM is referred to as Fleet DT.

3.1.4. Analysis Tools

The deterministic damage tolerance analysis, which must be performed prior to the risk analysis, is conducted using LifeWorks, a Boeing Proprietary tool for crack growth analysis.

The tool used to perform the risk analysis (calculation of SFPOF and other required information) is the Boeing Proprietary tool RBDMS (Risk-Based Design and Maintenance System). The methodology of this tool is discussed in the Risk Analysis section of this report, Section 0.

Microsoft Excel is used to conduct the cost/benefit analysis (CBA).

3.2. Example: Acquire Structural System Information

3.2.1. Fleet Parameters

The most important fleet parameter is the current flight load spectrum, FTA6, the most recent iteration of the usage experienced by the typical aircraft. This spectrum represents a significant increase in usage severity over the previous spectrum in the FSMP. Various other usage parameters provided by the F-15 program are as follows: the typical platform flies 300 flight hours (FH) per year at 1.3 FH per flight. The service life for the 300 aircraft fleet is assumed to be 18,000 FH, and this analysis is currently being conducted under the assumption that each platform is pristine. That is, this analysis is theoretically being conducted at the beginning of the life of the fleet. Note that the choice of an 18,000 FH service life will affect the analysis as costs will be spread over 60 years (300 FH per year). The sensitivity of the results of this analysis to the choice of lifetime is investigated in a later section of this document.

3.2.2. Maintenance Parameters

The F-15 Program has indicated that, in practice, maintenance actions are generally performed on multiples of 200 FH. For example, if an NDE inspection is scheduled to occur at 1116 FH, it will in actuality be performed at 1200 FH. Hence all traditional NDE inspections and repairs will take place on 200 FH increments. This requirement is relaxed with regard to the SHM system because its operation is not labor intensive.

Programmed Depot Maintenance (PDM) occurs every six calendar years (or 1800 FH intervals). PDM occurs at the depot (as opposed to in the field). At PDM the aircraft undergoes significant maintenance on several systems (including the structural system). Many locations in the wing cannot be accessed in the field due to significant obstruction of structure and materials. Therefore traditional NDE inspections and repairs cannot take place for certain locations outside of PDM.

In this document, locations are distinguished between those easily accessed in the field and those which can only be accessed in the depot. Field-accessible or *field* CPs can be accessed at any time. Depot-accessible or *depot* CPs can only be accessed at 1800 FH intervals.

3.2.3. Cost Parameters

Numerous cost parameters are required to conduct the cost/benefit analysis, such as the hourly labor rate for maintenance, the discount rate used for computing present and future values, etc. In addition, many of the parameters pertain to the installation and maintenance of an in-situ sensor system. Details of the inputs required by the cost model are discussed in Section 6.

3.3. Example: Acquire Control Point Information

The information specific to each individual CP required to conduct the risk and cost analyses are gathered at this stage of the process. Some of the required information is shown below in Table 2 and Table 3 to give the reader a sense of what information needs to be gathered. The tables are split by accessibility of the CPs. The accessibility is of paramount importance in determining a maintenance schedule as many locations can only be accessed in the depot when the aircraft is significantly disassembled for internal maintenance.

Not all of the data is shown in the tables. Additional data includes the medium and large crack repair times, the maximum stress scale parameter, the Kt standard deviation, and the NDE Probability of Detection (POD) slope (which is 0.5 for every CP). In addition to that data which can be tabulated, a damage tolerance / crack growth analysis is required for each CP, along with the Baseline inspection times. These are not included so that the report is kept brief.

Depot CP	Insp Time (hr)	Small Crack Repair Time (hr)	Failure Consequence	Part Cost ($)	Max Stress Location	Kt Mean	NDE POD Median
056	3.0	12	Loss of A/C	60000	18.30	45.2	0.050
059B	7.0	12	Loss of A/C	60000	1.40	45.2	0.050
097	2.0	12	Loss of A/C	100000	30.42	100.2	0.025
115	2.0	8	Replace Part	5000	16.25	32.2	0.025
124B	3.0	8	Loss of A/C	50000	11.58	45.2	0.050
126B	2.0	8	Loss of A/C	15000	28.09	39.2	0.025
131	2.5	12	Replace Part	5000	24.37	32.2	0.025
133A	1.0	6	Replace Part	500	54.45	32.2	0.025
134B	2.5	8	Replace Part	40000	21.75	45.2	0.025
135B	2.0	8	Replace Part	25000	127.00	45.2	0.025
137B	2.0	8	Replace Part	25000	72.57	45.2	0.025
138B	2.0	8	Replace Part	40000	23.05	45.2	0.025
141	2.0	8	Replace Part	5000	6.22	32.2	0.025
143	2.0	4	Replace Part	20000	79.45	80.0	0.025
144	2.0	24	Replace Part	5000	7.01	39.2	0.025
145	2.0	24	Replace Part	5000	7.01	39.2	0.025
179	2.5	8	Loss of A/C	60000	1.27	32.2	0.025
181	2.0	8	Loss of A/C	15000	1.30	30.0	0.025
182	2.0	8	Loss of A/C	15000	1.08	45.2	0.025
183	3.0	12	Loss of A/C	100000	0.97	100.2	0.050
192	3.0	8	Loss of A/C	15000	1.81	45.2	0.025
195	2.0	10	Loss of A/C	60000	1.04	45.2	0.025
196	2.0	8	Replace Part	5000	89.02	45.2	0.025
201	3.0	8	Loss of A/C	15000	109.20	45.2	0.025
202	3.0	12	Loss of A/C	60000	56.60	45.2	0.025
203	3.0	12	Loss of A/C	50000	1.06	45.2	0.025

Table 2. Example Control Point Information (Depot CPs)

Field CP	Insp Time (hr)	Small Crack Repair Time (hr)	Failure Consequence	Part Cost ($)	Max Stress Location	Kt Mean	NDE POD Median
054B	3.0	8	Replace Part	5000	8.37	32.2	0.025
054C	3.0	8	Replace Part	5000	8.37	32.2	0.025
055	2.0	8	Loss of A/C	50000	21.42	45.2	0.050
057B	2.0	8	Loss of A/C	60000	21.42	45.2	0.050
063B	3.0	12	Replace Part	5000	9.07	32.2	0.025
112B	3.0	12	Replace Part	25000	22.02	32.2	0.025
114	3.0	32	Replace Part	10000	7.58	39.2	0.025
116	2.5	8	Replace Part	5000	7.29	32.2	0.025
130B	3.0	32	Replace Part	10000	17.45	32.2	0.025
139	2.0	8	Replace Part	5000	18.78	32.2	0.025
140	2.0	8	Replace Part	5000	23.16	32.2	0.025
166B	3.0	24	Loss of A/C	100000	32.19	100.2	0.025
180	2.5	8	Loss of A/C	60000	1.08	32.2	0.025
184	2.0	8	Loss of A/C	40000	33.36	39.2	0.025
187	2.0	10	Loss of A/C	40000	20.05	39.2	0.025
188	2.0	8	Loss of A/C	40000	0.99	39.2	0.050
191	2.5	12	Replace Part	7500	89.10	39.2	0.025
194	3.0	12	Loss of A/C	25000	1.29	32.2	0.025

Table 3. Example Control Point Information (Field CPs)

3.4. Example: Define Parameters of Candidate Technology(s)

The capabilities of the SHM system were extensively detailed in the previous progress report. However, there have been some minor updates. The system characteristics and the associated assumptions are summarized here.

The SHM system is assumed to be similar in scope to traditional NDE inspections. That is, the crack detection capability is completely described by a POD Curve. The type of SHM system being considered can yield an infinite number of POD curves by changing the detection threshold of the software *without physically modifying the system*. The detection capability is directly related to the false alarm rate, because a system which is more likely to find a small crack is also more likely to falsely identify noise as a crack and thus report a false alarm. As the false alarm rate is a key parameter regarding the usage of the system, we have selected four false alarm rates (1%, 0.1%, 0.001%, and 0.0001%) and fit the POD curves to these values. The result is four separate SHM fidelity settings. These are referred to as the High, Medium, Intermediate, and Low fidelity settings (or simply H, M, I or L). The a_{90} value (or the crack size corresponding to 90% detection rate) is shown below in Table 4 along with the probability of false alarm – Pr(FA) – of each setting. See Figure 2 below for the POD curves.

Fidelity	Pr(FA)	a_{90} (in)
H	1.000%	0.0607
M	0.100%	0.0693
I	0.010%	0.0771
L	0.001%	0.0846

Table 4. SHM Fidelity Settings

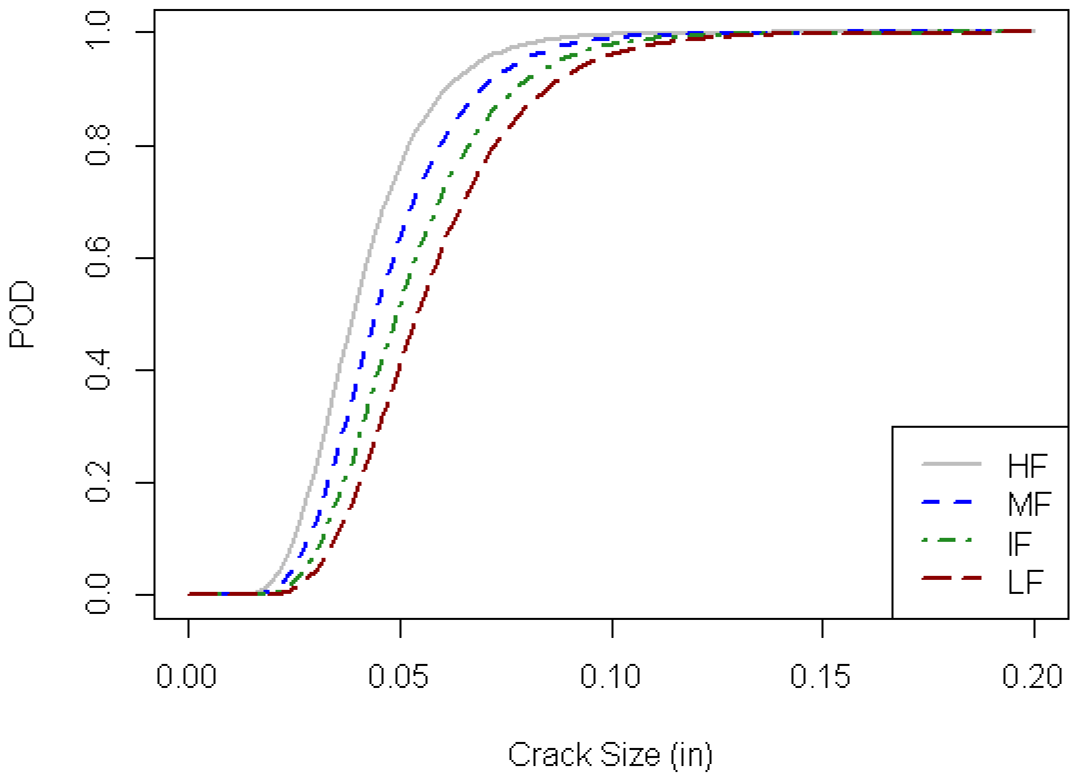

Figure 2. SHM POD Curves

Note that SHM inspections can occur at any time. However, for a depot CP, detection of a crack cannot lead to an immediate maintenance action *unless the aircraft is currently at the depot or is transported to the depot (at significant cost).* The in-situ inspections are assumed to take place at 200, 300, 600 or 900 FH intervals. These are chosen so that the intervals overlap those of the PDM cycle (1800 FH), allowing for immediate repairs at certain times without the associated transport penalties.

Finally, repeated inspections are assumed to be independent. This assumption may not be correct due to possible correlations between subsequent inspections utilizing the same built-in hardware. This is a technology gap which the team intends to address.

3.5. Example: Determine the Candidate Strategies for Each Control Point

A large number of inspection strategies are considered for each CP, including both NDE and SHM strategies.

Two special NDE strategies are the Baseline (currently implemented maintenance schedule) and the Threshold (NDE scheduled just prior to SFPOF reaching the 10^{-7} threshold). In the model, these are referred to as “nde_base” and “nde_threshold”. These strategies consist of variable intervals and are specific to each CP. In addition, constant interval NDE strategies are considered. In these, an inspection is performed at the indicated frequency. The naming convention is “nde_#”, where # is the flight hour interval between inspections. For example, nde_1800 includes ten inspections over the 18,000 FH service life, whereas nde_9000 calls for only two.

For depot CPs, these include nde_1800, nde_3600, nde_5400, nde_7200, and nde_9000. Recall, for depot locations NDE may only occur at PDM (1800 FH intervals). For field locations, NDE may be performed on 200 FH intervals, so the list is far longer: nde_200, nde_400, nde_600, ..., nde_8800, and nde_9000.

All SHM strategies occur on constant intervals. The naming convention is ”AB_#”, where A is the SHM fidelity utilized at the depot, B is the SHM fidelity used in the field, and # is the flight hour interval between inspections. For example, HL_600 indicates high fidelity inspections at the depot, low fidelity in the field, and 600 FH between inspections. All field locations utilize a single fidelity everywhere (that is, the strategy designation is HH, MM, II or LL) because the accessibility of the CP is not a concern and there is no need to differentiate between field and depot inspections.

Hence, there are 47 strategies for depot CPs and 63 strategies for Field CPs. These strategies are shown in Table 5.

Note that far more strategies could be generated by allowing for variable inspection intervals. For practical purposes, these are not utilized here. It may be possible to find a more optimal strategy by allowing for this, however, software capable of performing the risk and cost analyses simultaneously *for the entire system* would need to be developed, and a sophisticated optimization routine would be required. This is beyond the scope of this effort.

Field Strategies		Depot Strategies	
NDE	SHM	NDE	SHM
nde_0200	shm_HH_200	nde_1800	shm_HH_200
nde_0400	shm_HH_300	nde_3600	shm_HH_300
nde_0600	shm_HH_600	nde_5400	shm_HH_600
nde_0800	shm_HH_900	nde_7200	shm_HH_900
nde_1000	shm_MM_200	nde_9000	shm_HM_200
nde_1200	shm_MM_300	nde_base	shm_HM_300
nde_1400	shm_MM_600	nde_threshold	shm_HM_600
nde_1600	shm_MM_900		shm_HM_900
nde_1800	shm_II_200		shm_HI_200
nde_2000	shm_II_300		shm_HI_300
nde_2200	shm_II_600		shm_HI_600
nde_2400	shm_II_900		shm_HI_900
nde_2600	shm_LL_200		shm_HL_200
nde_2800	shm_LL_300		shm_HL_300
nde_3000	shm_LL_600		shm_HL_600
nde_3200	shm_LL_900		shm_HL_900
nde_3400			shm_MM_200
nde_3600			shm_MM_300
nde_3800			shm_MM_600
nde_4000			shm_MM_900
nde_4200			shm_MI_200
nde_4400			shm_MI_300
nde_4600			shm_MI_600
nde_4800			shm_MI_900
nde_5000			shm_ML_200
nde_5200			shm_ML_300
nde_5400			shm_ML_600
nde_5600			shm_ML_900
nde_5800			shm_II_200
nde_6000			shm_II_300
nde_6200			shm_II_600
nde_6400			shm_II_900
nde_6600			shm_IL_200
nde_6800			shm_IL_300
nde_7000			shm_IL_600
nde_7200			shm_IL_900
nde_7400			shm_LL_200
nde_7600			shm_LL_300
nde_7800			shm_LL_600
nde_8000			shm_LL_900
nde_8200			
nde_8400			
nde_8600			
nde_8800			
nde_9000			
nde_base			
nde_threshold			

Table 5. List of All Strategies for Field and Depot CPs

3.6. Example: Perform Control Point Risk Analyses

Each strategy described in the previous section has a corresponding RBDMS run. Section 0 of this report discusses the use of RBDMS for risk analysis. An example output file is shown in Table 6. Only those results which are utilized in the CBA are shown here.

No	CumFH	InspType	PFSLBI	PFSLAI	PCDsmall	PCDmed	PCDlarge
0	0	0	.1776E-14	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1	7200	1	.8451E-08	.1266E-13	.6098E-01	.6414E-01	.1213E-01
2	12600	1	.4988E-08	.1510E-13	.9438E-01	.8552E-01	.1469E-01
3	18000	1	.5242E-08	.4130E-13	.2104E+00	.2261E+00	.1677E-01

Table 6. Example RBDMS Output

`No` is the inspection number. `CumFH` is the flight hour at which the inspection occurs. `InspType` is the inspection type, which indicates the POD utilized at that inspection. This can be 0, 1 or 2, indicating no inspection, POD Type 1, or POD Type 2. The SFPOF before and after inspection are labeled `PFSLBI` and `PFSLAI`, respectively. The final three columns – `PCDsmall`, `PCDmed`, and `PCDlarge`, give the Probability of Crack Detection (PCD) for cracks of small, medium, or large size at each inspection. The user inputs the small/medium and medium/large crack size thresholds as RBDMS inputs and these are selected specifically for each CP based on the difficulty of repairs for various crack sizes. These are used in the cost model to predict the cost of future repairs.

Note that at time zero most of the values in the table are zero because no inspection is performed at that time. Even so, there is some risk of failure during the first flight because of assumed equivalent initial flaws assumed to exist prior to an aircraft being put into service.

3.7. Example: Determine Optimal Strategy(s) for Each Control Point

A strategy is required to maintain the risk below the 10^{-7} threshold in order to be considered. Those strategies which fail to do so are discarded. To find the optimal acceptable strategy, a component-level version of the CBA is utilized to estimate the inspection, repair, false alarm and cost of failure of each strategy. The optimal strategy must control the risk at 10^{-7} if possible. If, for example, no NDE strategy is capable of maintaining the risk below the threshold, the strategy with minimum peak risk is designated optimal.

We are explicitly choosing to use LCC as our criterion for comparison here. It would be equally valid to choose Fleet DT to find the optimal strategies for each CP. These TPMs tend to be correlated as lesser Fleet DT implies fewer repairs and failures have occurred (hence lower costs).

Note that this solution does not eliminate the need to conduct a system-level cost benefit analysis because the cost of the SHM system for a given CP is lower if there are other SHM CPs to help share the development costs. Thus, one cannot simply find the optimal solution for each CP because the decision to install SHM on an individual CP is dependent on the number of other SHM-enabled CPs in the system.

One can determine the optimal NDE strategy without regard for the number of SHM-enabled CPs in the system. In addition, one can ignore the SHM development costs and determine the optimal SHM strategy for each CP. This is due to the fact that if SHM were to be used on a CP, the SHM development and maintenance costs are the same regardless of

the fidelity utilized or the frequency of inspection. Therefore the optimal SHM strategy for that CP can be found independent of the system. With this pair of possible strategies (optimal NDE and optimal SHM) for each CP in hand, an exhaustive list of potential configurations can be created and cycled through the system level CBA to find the optimal configuration.

With 44 CPs in the system, considering two strategies for each is not feasible. This would require assessment of 2^{44}, or more than one million configurations! We need to eliminate either the NDE or SHM strategy from as many CPs as possible, and this can be done for various reasons:

- SFPOF > 10^{-7}
    - That is, if *every* SHM strategy fails to maintain the risk below the threshold, we may discard in favor of NDE (or vice versa)
- The LCC of the optimal SHM strategy is more expensive than the Optimal NDE strategy
    - If SHM is more expensive *before* including the SHM development costs, it is guaranteed that it will be more expensive after including them
- SHM is cheaper than NDE, but by less than the minimum SHM development cost
    - The minimum SHM development cost for a CP can be found by calculating the average per CP cost when *every possible CP has SHM installed*, which maximizes the cost sharing benefit
    - This criterion was not utilized in the following as the first two criteria did an excellent job of reducing the configuration list in this case

Note that for some CPs, no strategy of either NDE or SHM was capable of maintaining the risk threshold below 10^{-7}. This indicates that the risk at these locations is too high and either new technology must be considered or the parts must be redesigned. When working through the flowchart these CPs would normally be removed during the later step “Evaluate Alternate Technology(s) or Re-Design Problematic Control Points”. We remove them now for sake of simplicity so that we need not loop through the flowchart multiple times. There is additional discussion of these removed CPs in Section 3.13.

Following the rules above, we are able to reduce 21 of the remaining 34 CPs to one strategy. Hence 13 CPs have two competitive strategies, leading to a total number of acceptable configurations of 2^{13} = 8192. The other two configurations to be considered are the Baseline configuration and the Best NDE configuration, for a grand total of 8194 configurations. The Best NDE configuration represents the best we can do without utilizing the SHM technology. Each of these additional NDE-only configurations contain CP strategies with SFPOF > 10^{-7} in the service life so please keep in mind that according to our ground rules they are not acceptable configurations.

In Table 7, the remaining competitive strategies are shown in black and the discarded strategies are indicated (red strategies dropped due to risk; green strategies dropped due to LCC). The ten CPs removed due to high risk are not shown. In addition, one possible acceptable configuration consisting only of remaining strategies is shown in the rightmost column.

CP	Optimal NDE Strategies	Optimal SHM Strategies	An Acceptable Configuration
054B	nde_threshold	shm_MM_900	nde_threshold
054C	nde_threshold	shm_MM_900	nde_threshold
055	nde_0800	shm_LL_600	nde_0800
057B	nde_1200	shm_LL_900	nde_1200
063B	nde_threshold	shm_LL_900	nde_threshold
112B	nde_threshold	shm_LL_900	nde_threshold
114	nde_threshold	shm_II_200	nde_threshold
116	nde_0800	*shm_MM_200*	nde_0800
139	nde_0400	*shm_MM_200*	nde_0400
166B	nde_3200	shm_LL_900	nde_3200
180	nde_0600	*shm_MM_200*	nde_0600
184	nde_0200	shm_MM_200	nde_0200
188	nde_0400	shm_MM_300	nde_0400
194	nde_3000	shm_MM_900	nde_3000
056	nde_1800	shm_IL_900	nde_1800
059B	*nde_1800*	shm_HL_900	shm_HL_900
097	nde_9000	*shm_LL_900*	nde_9000
124B	nde_1800	shm_ML_900	nde_1800
134B	*nde_1800*	shm_HH_200	shm_HH_200
135B	nde_3600	*shm_HL_900*	nde_3600
137B	*nde_1800*	shm_HM_900	shm_HM_900
138B	*nde_1800*	shm_HL_300	shm_HL_300
143	*nde_1800*	shm_HL_900	shm_HL_900
144	*nde_1800*	shm_HL_200	shm_HL_200
179	*nde_1800*	shm_HL_600	shm_HL_600
181	nde_1800	*shm_HL_900*	nde_1800
182	nde_3600	*shm_HL_900*	nde_3600
183	*nde_1800*	shm_HL_900	shm_HL_900
192	nde_9000	*shm_HL_900*	nde_9000
195	nde_1800	*shm_HL_900*	nde_1800
196	nde_3600	*shm_HL_900*	nde_3600
201	nde_9000	*shm_HL_900*	nde_9000
202	nde_1800	*shm_HL_900*	nde_1800
203	nde_1800	*shm_HL_900*	nde_1800

dropped: risk
dropped: LCC

Table 7. Optimal Strategies, Dropped Strategies, and an Acceptable Configuration

3.8. Example: Select a Candidate System Configuration

We have 4096 configurations for which to evaluate the TPMs. In the project, the current step and the following two steps (the system-level risk and cost analyses) have been automated so that the TPMs of the complete list of configurations are calculated one-at-a-time as a batch. Here we identify one configuration for discussion. In Table 7, we have identified a single potential configuration which would be "acceptable". In this configuration we see that 8 CPs have SHM installed, and the remaining 26 have an NDE strategy.

3.9. Example: Perform System-Level Risk Analysis

The system-level risk analysis which calculates SFPOF for the structure as a whole has yet to be conducted in this project. At this stage we are utilizing an SFPOF threshold of 10^{-7} for each CP. Every strategy which remains in the analysis at this point has acceptable risk; therefore there is no action to be taken here.

3.10. Example: Perform System-Level Cost Analysis

The previous progress report details the use of the CBA (though it describes a slightly outdated version). Note that the team is creating a user manual for the cost/benefit model which will provide details regarding the use and extension of the CBA. Here we will simply point out that the goal of the CBA is to calculate the TPMs utilizing the risk analysis and various other assumptions as inputs. The general categories for cost sources are: inspections, repairs, false alarms, failures, and costs due to the SHM system. These are each some combination of labor, materials, transportation, or other miscellaneous costs.

As an example we can examine the results of the configuration shown in Table 7. Recall, this thirty-four (34) CP configuration does not include the ten CPs for which the SFPOF was too high for every strategy. Table 8 shows the components of the LCC in thousands of dollars for a single platform due to inspections, repairs, false alarms and failures (Insp, Rep, FA, and Fail). The table is first sorted by accessibility and then by LCC in descending order. Note that only the SHM strategies have costs associated with false alarms. This table does not depict 100% of the LCC as it does not include the SHM non-recurring and recurring costs.

The sum of LCC in the table is $4M. With three hundred (300) aircraft in the fleet, the total LCC of inspections repairs, false alarms and failures is $1.2B. The non-recurring SHM costs for this configuration (which includes eight SHM locations) are $7M and the recurring costs are $31M. These SHM development costs are in addition to the costs shown in Table 8.

In the rightmost column we find the percentage of the total LCC (not including SHM costs) due to each CP. Note that a handful of locations are responsible for the majority of the expected costs. The first CP in the list, 134B, has strategy shm_HH_200. Note that 134B is a depot location. NDE may only be conducted on 1800 FH intervals. This is too infrequent to maintain SFPOF below 10^{-7}, and high fidelity SHM is required to control the risk. Much of the cost is due to the penalties that are applied to depot-accessible locations for maintenance actions when the aircraft is away from the depot. This is shown in Section 3.14.

Access	CP	Strategy	Costs ($thousands) Insp LCC	Rep LCC	FA LCC	Fail LCC	Sum LCC	% of Total Sum of LCC
Depot	134B	shm_HH_200	0.9	799.8	251.8	0.0	1052.5	26%
Depot	097	nde_9000	0.4	816.8	0.3	0.1	817.6	20%
Depot	138B	shm_HI_300	0.1	405.3	15.5	0.3	421.2	11%
Depot	183	shm_HL_200	0.0	393.9	7.1	0.0	401.0	10%
Depot	179	shm_ML_600	0.0	231.9	6.7	0.0	238.6	6%
Depot	059B	shm_ML_200	0.0	128.0	3.7	0.0	131.8	3%
Depot	181	nde_1800	0.2	116.0	0.0	2.6	118.7	3%
Depot	195	nde_1800	0.9	69.7	0.4	0.0	71.1	2%
Depot	202	nde_1800	0.0	63.8	0.1	0.0	63.9	2%
Depot	137B	shm_HL_600	1.4	13.9	0.0	5.0	20.4	1%
Depot	143	shm_HL_900	1.4	13.1	0.0	0.0	14.6	0%
Depot	144	shm_IL_200	2.2	10.1	0.0	0.0	12.3	0%
Depot	135B	nde_3600	0.6	6.2	0.0	0.0	6.8	0%
Depot	182	nde_3600	0.6	4.8	0.0	0.0	5.5	0%
Depot	201	nde_9000	0.2	4.5	0.0	0.1	4.8	0%
Depot	192	nde_9000	0.2	3.3	0.0	0.6	4.2	0%
Depot	203	nde_1800	2.2	1.5	0.0	0.0	3.7	0%
Depot	056	nde_1800	2.2	0.2	0.0	0.1	2.4	0%
Depot	124B	nde_1800	2.2	0.1	0.0	0.0	2.2	0%
Depot	196	nde_3600	0.6	1.3	0.0	0.0	1.9	0%
Field	180	nde_0600	5.8	219.7	0.0	0.4	225.8	6%
Field	114	nde_threshold	4.3	157.0	0.0	0.0	161.3	4%
Field	184	nde_0200	14.2	66.1	0.0	0.2	80.5	2%
Field	139	nde_0400	7.0	60.1	0.0	0.0	67.1	2%
Field	116	nde_0800	4.4	22.9	0.0	0.0	27.3	1%
Field	188	nde_0400	7.0	18.2	0.0	0.0	25.3	1%
Field	112B	nde_threshold	1.4	3.6	0.0	0.0	5.1	0%
Field	055	nde_0800	3.5	0.3	0.0	1.1	4.9	0%
Field	194	nde_3000	1.2	1.9	0.0	0.2	3.3	0%
Field	057B	nde_1200	2.2	0.2	0.0	0.2	2.6	0%
Field	054C	nde_threshold	1.9	0.5	0.0	0.0	2.4	0%
Field	054B	nde_threshold	1.2	0.5	0.0	0.0	1.7	0%
Field	166B	nde_3200	1.2	0.0	0.0	0.1	1.3	0%
Field	063B	nde_threshold	0.7	0.5	0.0	0.0	1.2	0%

Total	72.3	3635.7	285.6	11.0	4005.0
% of Total	2%	91%	7%	0%	100%

Table 8. Per Platform Costs for an Optimal Configuration in Thousands of Dollars

3.11. Example: Analyzed All Candidate Configurations?

In the case of this analysis, when the automated process for calculating the TPMs has been completed, we may move onto the next step.

3.12. Example: TPM Results Acceptable For At Least One Configuration?

Bear in mind that we have already removed the ten high risk CPs from consideration and that we do not have a system-level risk requirement in place. For these reasons, all of the configurations constructed from the list of acceptable strategies are acceptable.

3.13. Example: Evaluate Alternate Technology(s) or Re-Design Problematic Control Points

This is the step in which we formally recommend redesign for the ten high risk CPs before stepping back through the analysis. Rather than loop through the flowchart in this document, we stepped through assuming this step had already taken place.

Note that in some cases one may choose to utilize a more capable technology or to examine different possible technologies. For these ten CPs and the findings we have in hand, we must recommend re-design because the risk is simply too great to mitigate via inspection and repair. That said, there is reason to believe that there remains significant conservatism in this analysis and the reader should not view these results as evidence that the F-15 is poorly designed. Rather, this should be viewed as evidence that much work remains to be done to unwind the decades of conservatism built into every phase of the traditional design and analysis of aircraft structures before accurate reliability analysis can be performed.

Table 9 shows the peak value of SFPOF for the safest strategy of each of the ten CPs which are removed from consideration. Note that several of these strategies have SFPOF greater than 10^{-1}, or 10%. That is, it is being predicted that the probability of failure for several locations is over 10% *per flight*. This is not happening in the fleet; hence, these calculated risks cast some doubt on the accuracy of the results of the risk analysis. There is additional discussion of the conservatism of the risk analysis results located in Section 0.

CP	Insp Type	Strategy	Max(SFPOF)
130B	nde	nde_0200	2.86E-05
130B	shm	shm_HH_200	2.86E-05
140	nde	nde_threshold	4.40E-06
140	shm	shm_HH_200	4.40E-06
187	nde	nde_threshold	2.81E-07
187	shm	shm_HH_200	2.81E-07
191	nde	nde_threshold	5.83E-07
191	shm	shm_HH_200	5.83E-07
115	nde	nde_1800	5.00E-01
115	shm	shm_HH_200	2.27E-05
126B	nde	nde_1800	4.91E-02
126B	shm	shm_HH_200	1.45E-07
131	nde	nde_1800	1.00E+00
131	shm	shm_HH_200	9.93E-02
133A	nde	nde_1800	9.62E-01
133A	shm	shm_HH_200	1.15E-01
141	nde	nde_1800	9.97E-01
141	shm	shm_HH_200	9.48E-05
145	nde	nde_1800	1.07E-04
145	shm	shm_HH_200	2.93E-05

Table 9. Optimal Strategies for Removed Control Points (Unacceptable Risk)

3.14. Example: Select Optimal System Configuration

The results of the automated run through of the system-level cost/benefit analysis consist of a large table of TPMs for each candidate configuration. In this case the optimal system configuration is found by choosing a TPM and searching the table for the configuration which achieves the optimal value. The configuration which achieves the minimum LCC is that which was previously shown in Table 7 and Table 8 above, and we refer to this as the Optimal configuration. Recall, this contains a mix of both NDE and SHM strategies.

We additionally discuss two other configurations which do not include SHM, the Baseline and Best NDE configurations. The Baseline configuration consists of the current fleet NDE maintenance strategies for the 34 CPs remaining in the system. The Best NDE configuration consists of the optimal NDE strategy for each CP. For CPs which successfully maintain SFPOF < 10^{-7}, the optimal strategy is that which minimizes LCC, and for CPs which cannot maintain the risk below the threshold, the safest strategy is considered optimal.

Note that for the Baseline, 26 of the 34 CPs have SFPOF which exceeds 10^{-7}, and for the Best NDE, 8 of the 34 CPs exceed this criterion. Under the ground rules set forth in this analysis, neither the Baseline nor the Best NDE configuration would be an acceptable maintenance plan. Of the three configurations discussed in this section, only the Optimal configuration is acceptable because those strategies in which SFPOF exceeds 10^{-7} were not considered.

It is interesting to note that the Optimal configuration suggests the use of SHM on *only* those 8 CPs for which NDE was not possible. That is, in this analysis, SHM did not prove to be worth the investment for those CPs which can successfully be managed with NDE. This is due in large part to the high cost associated with the need to transport the aircraft to the depot for unscheduled maintenance of depot-accessible locations (inaccessibility labor penalty).

We focus on the NPV of costs (that is, discounted costs) as this allows for fair comparison of costs dispersed through a long period of time. Table 10 shows the costs for each configuration. Note that the Baseline costs are significantly higher than the other configurations. The results are summarized graphically in Figure 3. Inspection, repair false alarm and failure costs in Table 10 are again abbreviated Insp, Rep, FA and Fail. The Baseline is omitted from the graph because the large costs completely dominate the chart. In both the table and the chart one can see that the inaccessibility labor penalty has a substantial effect on the resulting costs; particularly the repair costs.

	Baseline	Best NDE	Optimal (w/ Penalty)	Optimal (w/o Penalty)
Insp NPV ($)	4,274,666	12,063,960	10,122,336	10,122,336
Rep NPV ($)	221,900,048	166,360,533	466,280,489	145,561,014
FA NPV ($)	–	–	39,964,278	4,508,808
Fail NPV ($)	22,045,544,782	156,981,583	1,499,022	1,492,270
NPV ($)	22,271,719,496	335,406,076	539,075,940	182,894,243
LCC ($)	62,406,074,791	810,621,751	1,239,958,150	432,024,882
Fleet DT (hr)	17,411,660	360,289	460,603	460,603
# SHM CPs	–	–	8	8
Total SHM NPV ($)	–	–	21,209,815	21,209,815

Table 10. TPMs and Discounted Cost Components for Several Configurations

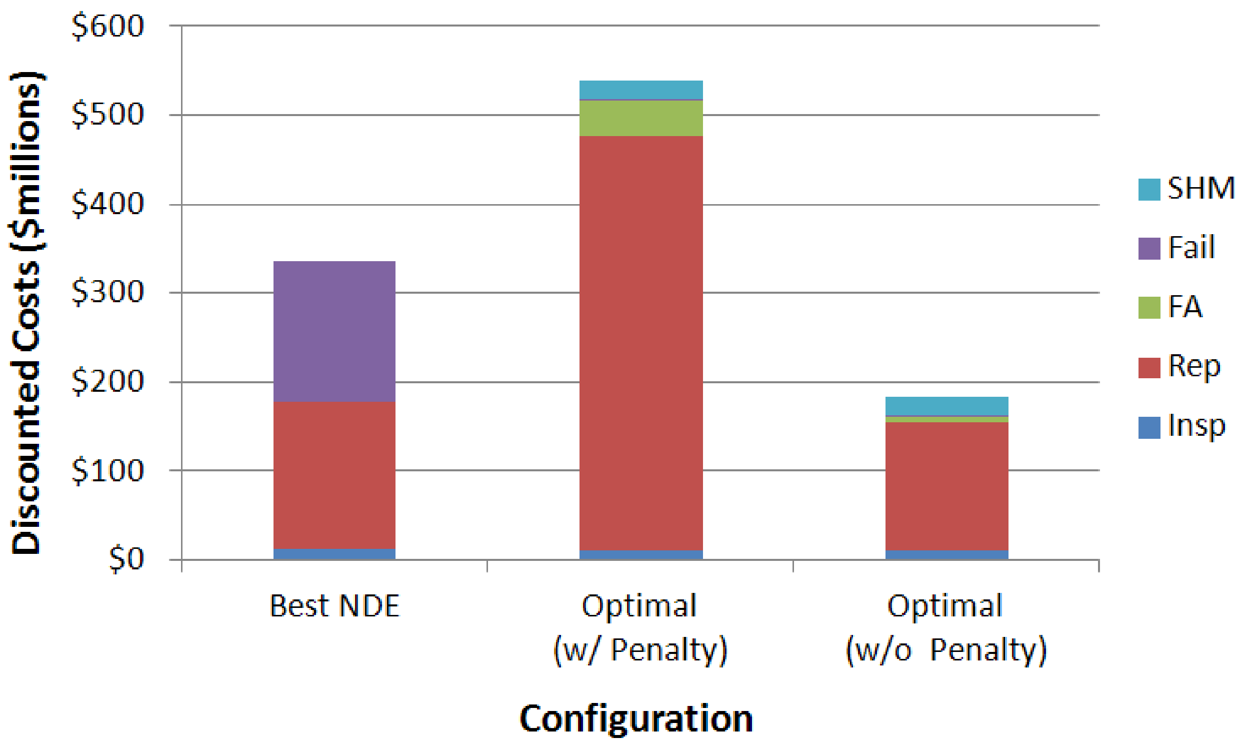

Figure 3. Discounted Cost Components for Several Configurations

3.15. Example: Conclusions

There are a number of conclusions to draw from the data shown in this example analysis. These are summarized below.

- The large SFPOF of many CPs in the Baseline configuration leads to excessive failure prediction and high associated costs
    - The SFPOF results are likely highly conservative (see Section 0)
- The majority of the failure cost predictions of the Best NDE configuration are due to the depot locations for which NDE inspection at 1800 FH is insufficient to control the risk
    - For these CPs the increased frequency of SHM removes the failure risk
- In this case, the SHM non-recurring and recurring costs are a small part of the cost predictions for the Optimal configuration
- The inaccessibility labor penalty is a highly influential parameter

4. In-Situ Sensor Capability Analysis

4.1. Overview

Thus far the capability of the SHM's in-situ sensors used in the analysis has been considered constant throughout the lifetime of these sensors. That is, it has been assumed that the sensors will not degrade. However, in the present cost analysis, the sensors for each location are assumed to be replaced five times within the lifespan of the design. In other words, all the sensors will be replaced on average every 12 years based on the 5 replacements in 60 years lifespan assumption. This suggests that some degradation of SHM capability is expected to occur within these 12 year periods.

For this program, research for the SHM degradation model will be focused on the following areas based on available resources:

1. Develop a SHM degradation model and determine its impact on the POD capability
2. Assess the impact of selected SHM degradation model parameters on the following:
    a. Single flight probability of failure (SFPOF)
    b. Probability of crack detection (PCD)
3. Integrate with Cost Benefit Analysis (CBA) to assess the impact of SHM degradation model with consideration of sensor replacement schedule. A sensitivity study will be performed by considering various POD degradation limits and replacement schedules. Based on sensitivity study results, define the following requirements for the POD degradation model.
    a. SHM POD capability degradation limit
    b. Sensor reliability
    c. Sensor replacement schedule.

4.2. SHM Degradation Model Development

The degradation model of the physical system (i.e. sensors) is currently not available and to develop such a model for the physical system is not part of the Statement of Work. In addition, there are no projects currently working on this issue except a few references [20, 21] identified. Based on available resources (research papers and hot spot project experience), the degradation of POD's parameters is assumed to assess the impact of SHM degradation on the overall risk, inspection and repair, and cost.

The current degradation model for SHM POD is defined as follows,

$$POD(a)_{Degraded} = \Phi\left(\frac{\ln(a)-\mu}{\sigma}\right)$$

$$= \Phi\left(\frac{\ln(a - a\min) - \ln(amed * \alpha_d)}{asteep * \beta_d}\right) * POI$$

Based on the above SHM POD model, it is important to relate these parameters to the Least Square parameters used to create the SHM POD model, which can be developed based on crack length, damage index and noise level. As shown in the Figure 4, a number of damage index vs. crack size data have been plotted and a least square fit has been performed to define the POD model.

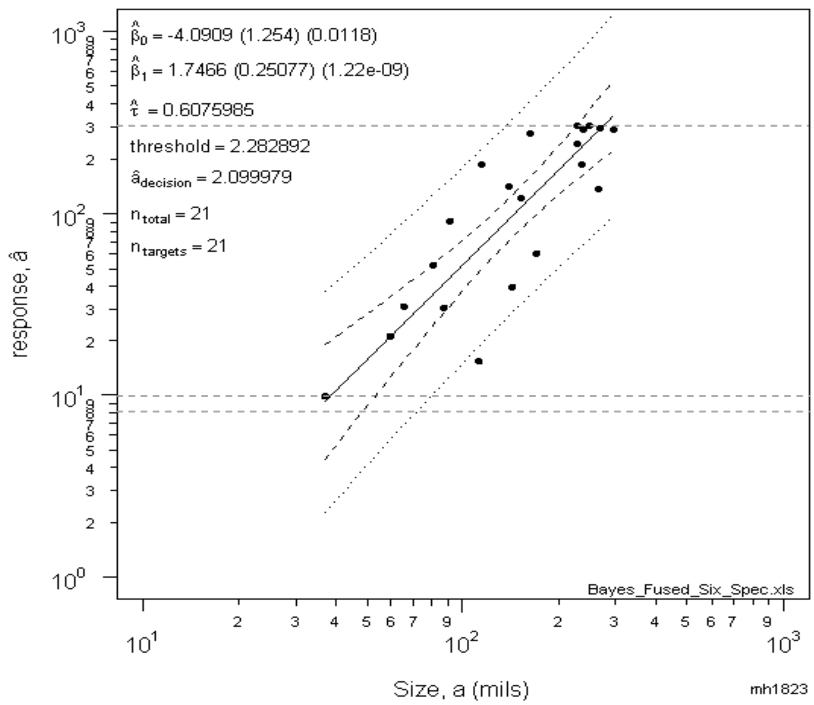

Figure 4. Least Square Fit Results [log(â) = $\beta_1$log(a) + β_0 + ε]

Based on the above least square results, the POD curve's parameters can be derived as follows:

$$POD(a) = \Phi\left(\frac{\ln(a) - \mu}{\sigma}\right) = \Phi\left(\frac{\ln(a) - \left(\frac{y_{th} - \beta_0}{\beta_1}\right)}{\left(\frac{\tau}{\beta_1}\right)}\right)$$

$$= \Phi\left(\frac{\beta_1 * \ln(a) - y_{th} + \beta_0}{\tau}\right) = \Phi\left(\frac{\beta_0 + \beta_1 * \ln(a) - y_{th}}{\tau}\right)$$

$$= \Phi\left(\frac{\ln(a - a\min) - \ln(amed)}{asteep}\right) * POI$$

$$where,$$

$$amed = \exp\left(\frac{y_{th} - \beta_0}{\beta_1}\right)$$

$$asteep = \left(\frac{\tau}{\beta_1}\right)$$

Based on the above function, various SHM POD curves have been developed with consideration of various false alarm probabilities as shown in Table 11 and Figure 5. Notice that the impact of false alarm could be derived from the selection of the threshold values.

	amed	asteep	Prob. (False Alarm)	Threshold (mils)	a50	a90
Ultra High	0.0346	0.3479	5.000%	8.17	0.0346	0.0541
High	0.0389	0.3479	1.000%	10.01	0.0389	0.0608
Medium	0.0443	0.3479	0.100%	12.57	0.0443	0.0692
Intermediate	0.0493	0.3479	0.010%	15.16	0.0493	0.0770
Low	0.0542	0.3479	0.001%	17.84	0.0542	0.0846

Table 11. Various SHM Parameters for Different False Alarm Probabilities

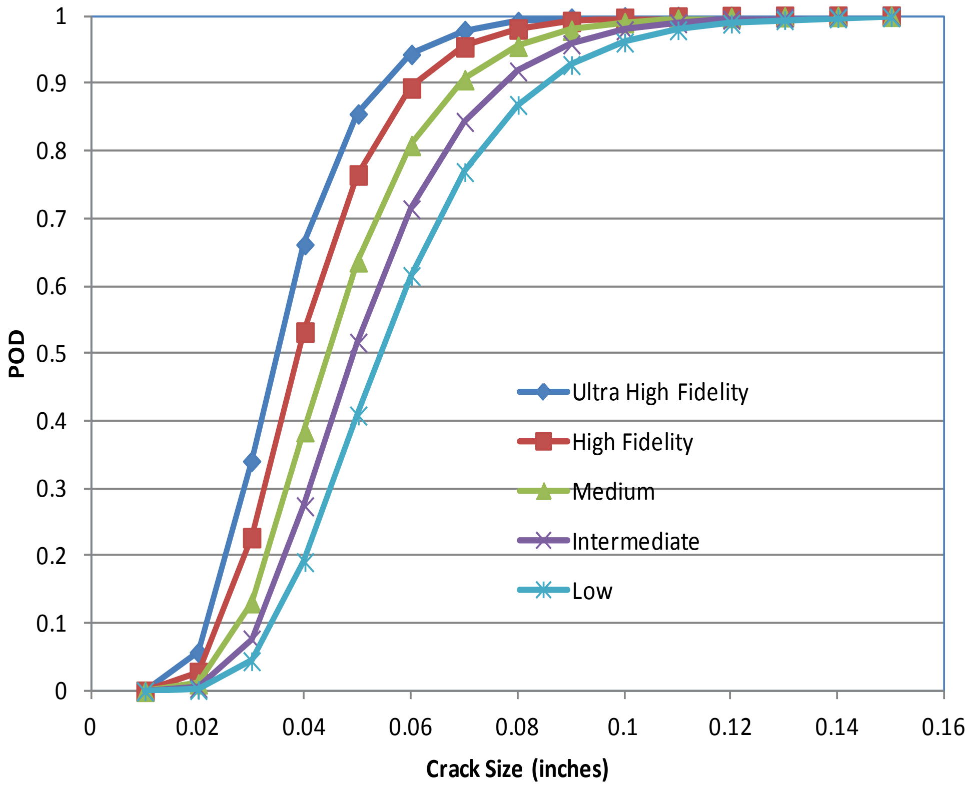

Figure 5. Various SHM POD Curves

With consideration of degradation parameters for both amed and asteep, the following degradation parameters for the least square fit parameters can be derived:

$$POD(a)_{Degraded} = \Phi\left(\frac{\ln(a)-\mu}{\sigma}\right)_{Degraded}$$

$$= \Phi\left(\frac{\ln(a)-\ln(amed*\alpha_d)}{asteep*\beta_d}\right) = \Phi\left(\frac{\ln(a)-\left(\frac{y_{th}-\beta_0*\kappa_d}{\beta_1}\right)}{\left(\frac{\tau*\lambda_d}{\beta_1}\right)}\right)$$

$$= \Phi\left(\frac{\ln(a)*\beta_1-\left(y_{th}-\beta_0*\kappa_d\right)}{\tau*\lambda_d}\right)$$

$$where,$$

$$amed*\alpha_d = \exp\left(\frac{y_{th}-\beta_0*\kappa_d}{\beta_1}\right)$$

$$\alpha_d = \left(\frac{1}{amed}\right)\exp\left(\frac{y_{th}-\beta_0*\kappa_d}{\beta_1}\right)$$

$$or$$

$$\kappa_d = \frac{1}{\beta_0}\left(y_{th}-\beta_1*\ln(amed*\alpha_d)\right)$$

$$and$$

$$asteep*\beta_d = \left(\frac{\tau*\lambda_d}{\beta_1}\right)$$

$$\beta_d = \frac{1}{asteep}\left(\frac{\tau*\lambda_d}{\beta_1}\right)$$

$$\lambda_d = \frac{1}{\tau}\left(\beta_1*\left(asteep*\beta_d\right)\right)$$

Using the formulas for *amed* and β_0 above, the results in Table 12 were derived. Or both parameters in reverse, the results in Table 13 were derived.

	amed	$\beta 0$	% change in $\beta 0$
Original	0.0389	-4.0910	
5% change in amed	0.0409	-4.1762	2.08
10% change in amed	0.0428	-4.2575	3.99
15% change in amed	0.0447	-4.3351	5.73
20% change in amed	0.0467	-4.4095	7.35
25% change in amed	0.0486	-4.4808	8.84

Table 12. amed and β_0 Relationship

	amed	asteep	% changes in amed
Original	0.0389	0.3479	
5% change in $\beta 0$	0.0437	0.3479	12.42%
10% change in $\beta 0$	0.0492	0.3479	26.39%
15% change in $\beta 0$	0.0553	0.3479	42.10%
20% change in $\beta 0$	0.0622	0.3479	59.75%
25% change in $\beta 0$	0.0699	0.3479	79.60%

Table 13. β_0 and amed Relationship

To demonstrate the degradation impact, the following data are calculated based on the original β_0 and a 5% increase in β_0. The main purpose of Table 14 and Figure 6 is to demonstrate the degradation in original β_0 will have a linear degradation to the least square fit results. As shown above, with the 5% increase in β_0 will cause the amed to increase by 12.42%. Also shown in Figure 7 is the corresponding POD plot given an increase in β_0.

a	Original $\beta 0 = -4.091$	5% increase $\beta 0 = -4.29555$
30	6.356839671	5.180913265
60	21.33144366	17.38542501
90	43.30930769	35.29769168
120	71.58124354	58.33971492
150	105.6969043	86.14445571
180	145.3316593	118.4473355
210	190.2345935	155.0438551
240	240.2028906	195.7687163
270	295.0673967	240.4840564
300	354.6837226	289.072196
330	418.9263925	341.4308708
360	487.6848028	397.4699371

Table 14. β_0 Impact to Least Square Fit Results

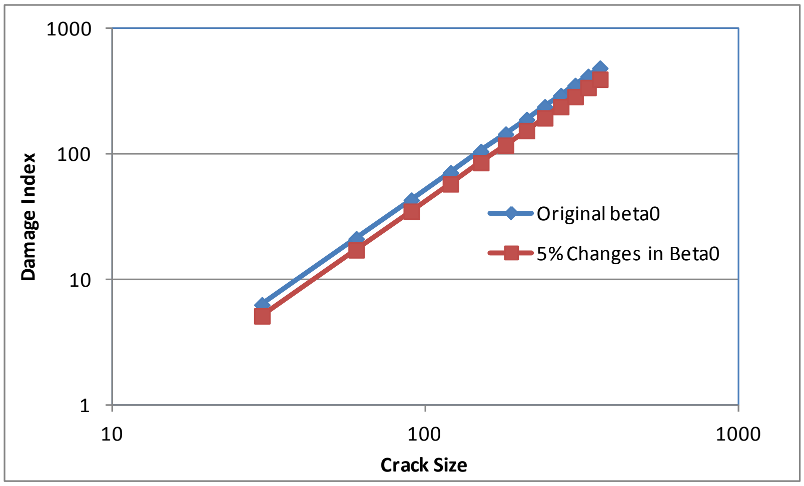

Figure 6. β_0 Impact to Least Square Fit Results

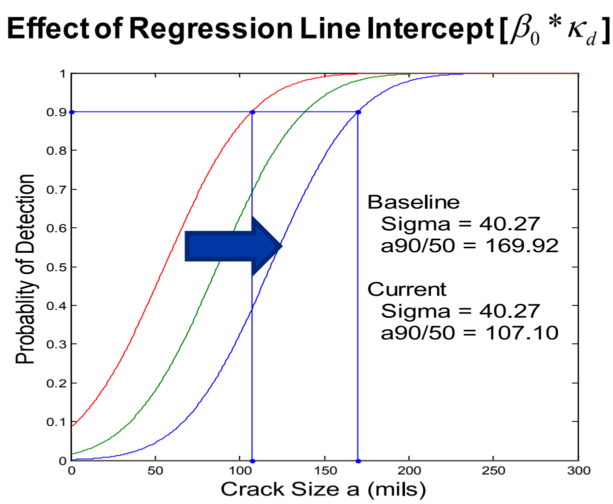

Figure 7. β_0 or amed Impact to Probability of Detection Results

Also, given the asteep and τ relationship, the following Table 15 and Figure 8 were derived:

	amed	asteep	% change in asteep
Original	0.0389	0.3479	
5% change in τ	0.0389	0.3653	5.00
10% change in τ	0.0389	0.3827	10.00
15% change in τ	0.0389	0.4001	15.00
20% change in τ	0.0389	0.4175	20.00
25% change in τ	0.0389	0.4348	25.00

Table 15. asteep and τ Relationship

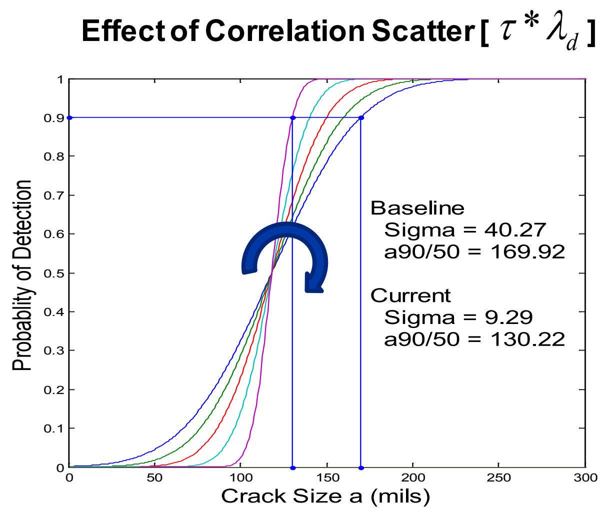

Figure 8. *asteep or* τ Impact to Probability of Detection Results

4.3. Assess The Impact of SHM Degradation

This section summarizes the impact of SHM degradation based on the POD parameters (amed and asteep) as discussed in section 4.2. The demonstration example used is the bulkhead example.

4.3.1. amed Impact

To demonstrate the impact of amed, different percentages of degradation, i.e., from 25 to 5 without consideration of replacement of sensor set are considered. The results show that when a higher degradation percentage is used, the risk (SFPOF) gets increased accordingly. Higher degradation (amed) decreases the PCD accordingly.

Time	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After
0	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00
500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2500	2.38E-12	4.00E-15	2.28E-12	4.00E-15	2.16E-12	4.00E-15	2.05E-12	4.00E-15	1.84E-12	4.00E-15
3000	2.56E-10	4.00E-15	2.38E-10	4.00E-15	2.22E-10	4.00E-15	2.09E-10	4.00E-15	1.94E-10	4.00E-15
3500	4.91E-09	2.40E-14	4.50E-09	2.00E-14	4.19E-09	1.40E-14	3.84E-09	1.40E-14	3.53E-09	7.99E-15
4000	3.54E-08	2.30E-13	3.22E-08	1.88E-13	2.91E-08	1.56E-13	2.64E-08	1.28E-13	2.39E-08	1.04E-13
4500	1.26E-07	9.25E-13	1.11E-07	7.37E-13	9.89E-08	6.00E-13	8.81E-08	4.76E-13	7.87E-08	3.80E-13
5000	3.47E-07	2.63E-12	3.07E-07	2.05E-12	2.69E-07	1.62E-12	2.32E-07	1.26E-12	2.07E-07	9.85E-13
5500	7.11E-07	5.82E-12	6.14E-07	4.44E-12	5.30E-07	3.42E-12	4.56E-07	2.57E-12	3.97E-07	1.96E-12
6000	1.38E-06	1.18E-11	1.19E-06	8.75E-12	1.01E-06	6.57E-12	8.58E-07	4.81E-12	7.25E-07	3.55E-12
6500	2.34E-06	2.12E-11	1.98E-06	1.54E-11	1.66E-06	1.12E-11	1.38E-06	8.00E-12	1.16E-06	5.75E-12
7000	3.92E-06	3.65E-11	3.27E-06	2.59E-11	2.67E-06	1.84E-11	2.20E-06	1.28E-11	1.80E-06	8.92E-12
7500	5.33E-06	5.33E-11	4.37E-06	3.69E-11	3.58E-06	2.56E-11	2.88E-06	1.73E-11	2.31E-06	1.17E-11
8000	7.49E-06	7.71E-11	6.05E-06	5.22E-11	4.87E-06	3.65E-11	3.91E-06	2.34E-11	3.05E-06	1.54E-11
Cases:	amed = 25, No		amed = 20, No		amed = 15, No		amed = 10, No		amed = 5, No	

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 16. SFPOF Comparison for Degradation Parameter amed

Time	PCD	PCD	PCD	PCD	PCD
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
500	4.46E-06	4.50E-06	4.54E-06	4.58E-06	4.62E-06
1000	9.47E-06	9.62E-06	9.77E-06	9.93E-06	1.01E-05
1500	2.05E-05	2.09E-05	2.14E-05	2.18E-05	2.23E-05
2000	4.45E-05	4.56E-05	4.67E-05	4.79E-05	4.90E-05
2500	9.40E-05	9.64E-05	9.89E-05	1.01E-04	1.04E-04
3000	1.85E-04	1.90E-04	1.95E-04	2.00E-04	2.05E-04
3500	3.37E-04	3.45E-04	3.53E-04	3.62E-04	3.71E-04
4000	5.65E-04	5.77E-04	5.91E-04	6.04E-04	6.19E-04
4500	8.83E-04	9.01E-04	9.21E-04	9.41E-04	9.62E-04
5000	1.30E-03	1.33E-03	1.35E-03	1.38E-03	1.41E-03
5500	1.80E-03	1.83E-03	1.86E-03	1.90E-03	1.93E-03
6000	2.34E-03	2.38E-03	2.42E-03	2.46E-03	2.50E-03
6500	2.92E-03	2.96E-03	3.01E-03	3.06E-03	3.11E-03
7000	3.55E-03	3.60E-03	3.66E-03	3.71E-03	3.77E-03
7500	4.21E-03	4.27E-03	4.33E-03	4.39E-03	4.45E-03
8000	4.87E-03	4.93E-03	5.00E-03	5.07E-03	5.14E-03
Cases:	amed = 25, No	amed = 20, No	amed = 15, No	amed = 10, No	amed = 5, No

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 17. PCD Comparison for Degradation Parameter amed

4.3.2. asteep Impact

To demonstrate the impact of asteep, different percentages of degradation, i.e., from 25 to 5 without consideration of replacement of sensor set are used. The results shown that when a higher degradation percentage is used, the risk will increases as shown in Table 18. For PCD, higher degradation (asteep) increases the PCD. The impact is totally opposite of amed's impact as shown in Table 19.

Time	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After
0	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00
500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2500	2.26E-12	4.00E-15	2.23E-12	4.00E-15	2.13E-12	4.00E-15	2.02E-12	4.00E-15	1.95E-12	4.00E-15
3000	2.39E-10	4.00E-15	2.29E-10	4.00E-15	2.16E-10	4.00E-15	2.04E-10	4.00E-15	1.93E-10	4.00E-15
3500	4.61E-09	3.80E-14	4.27E-09	3.00E-14	4.00E-09	2.20E-14	3.74E-09	1.40E-14	3.50E-09	1.20E-14
4000	3.22E-08	3.82E-13	2.98E-08	2.62E-13	2.74E-08	2.00E-13	2.53E-08	1.52E-13	2.33E-08	1.16E-13
4500	1.11E-07	1.42E-12	1.02E-07	1.06E-12	9.21E-08	7.83E-13	8.39E-08	5.80E-13	7.77E-08	4.30E-13
5000	2.98E-07	4.13E-12	2.71E-07	3.00E-12	2.41E-07	2.14E-12	2.18E-07	1.54E-12	1.98E-07	1.10E-12
5500	5.95E-07	9.41E-12	5.31E-07	6.64E-12	4.82E-07	4.61E-12	4.31E-07	3.21E-12	3.83E-07	2.19E-12
6000	1.14E-06	2.20E-11	1.00E-06	1.33E-11	8.88E-07	9.00E-12	7.93E-07	6.06E-12	6.97E-07	4.02E-12
6500	1.85E-06	3.57E-11	1.65E-06	2.39E-11	1.44E-06	1.57E-11	1.26E-06	1.02E-11	1.11E-06	6.54E-12
7000	2.97E-06	6.92E-11	2.62E-06	4.09E-11	2.29E-06	2.62E-11	1.98E-06	1.65E-11	1.70E-06	1.02E-11
7500	4.02E-06	1.07E-10	3.49E-06	6.53E-11	2.98E-06	3.70E-11	2.57E-06	2.27E-11	2.19E-06	1.36E-11
8000	5.43E-06	1.41E-10	4.69E-06	8.55E-11	4.05E-06	5.19E-11	3.44E-06	3.09E-11	2.88E-06	1.79E-11
Cases:	asteep = 25, No		asteep = 20, No		asteep = 15, No		asteep = 10, No		asteep = 5, No	

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 18. SFPOF Comparison for Degradation Parameter asteep

Time	PCD	PCD	PCD	PCD	PCD
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
500	4.97E-06	4.91E-06	4.84E-06	4.78E-06	4.72E-06
1000	1.14E-05	1.12E-05	1.09E-05	1.07E-05	1.05E-05
1500	2.60E-05	2.53E-05	2.46E-05	2.40E-05	2.34E-05
2000	5.74E-05	5.59E-05	5.45E-05	5.30E-05	5.16E-05
2500	1.21E-04	1.18E-04	1.15E-04	1.12E-04	1.09E-04
3000	2.35E-04	2.30E-04	2.25E-04	2.20E-04	2.15E-04
3500	4.21E-04	4.12E-04	4.04E-04	3.95E-04	3.88E-04
4000	6.94E-04	6.81E-04	6.69E-04	6.57E-04	6.45E-04
4500	1.07E-03	1.05E-03	1.03E-03	1.02E-03	1.00E-03
5000	1.54E-03	1.52E-03	1.50E-03	1.48E-03	1.46E-03
5500	2.10E-03	2.07E-03	2.05E-03	2.02E-03	1.99E-03
6000	2.71E-03	2.67E-03	2.64E-03	2.61E-03	2.58E-03
6500	3.35E-03	3.31E-03	3.27E-03	3.23E-03	3.20E-03
7000	4.05E-03	4.00E-03	3.95E-03	3.91E-03	3.87E-03
7500	4.76E-03	4.71E-03	4.66E-03	4.61E-03	4.56E-03
8000	5.50E-03	5.44E-03	5.38E-03	5.32E-03	5.27E-03
Cases:	asteep = 25, No	asteep = 20, No	asteep = 15, No	asteep = 10, No	asteep = 5, No

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 19. PCD Comparison for Degradation Parameter asteep

4.3.3. Both amed and asteep Impact

To demonstrate the impact of both amed and asteep individually and combined, several cases including the baseline case without consideration of sensor replacement are used. The results shown that amed has more impact on risk given the same percentage of degradation for amed or asteep as shown in Table 20. For PCD, asteep's impact is higher than amed as shown in Table 21.

Time	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After
0	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00
500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2500	1.80E-12	4.00E-15	2.38E-12	4.00E-15	2.26E-12	4.00E-15	2.90E-12	4.00E-15
3000	1.80E-10	4.00E-15	2.56E-10	4.00E-15	2.39E-10	4.00E-15	3.30E-10	4.00E-15
3500	3.21E-09	9.99E-15	4.91E-09	2.40E-14	4.61E-09	3.80E-14	6.85E-09	9.19E-14
4000	2.16E-08	8.59E-14	3.54E-08	2.30E-13	3.22E-08	3.82E-13	5.15E-08	8.55E-13
4500	7.03E-08	3.02E-13	1.26E-07	9.25E-13	1.11E-07	1.42E-12	1.92E-07	3.98E-12
5000	1.80E-07	7.65E-13	3.47E-07	2.63E-12	2.98E-07	4.13E-12	5.50E-07	1.29E-11
5500	3.38E-07	1.47E-12	7.11E-07	5.82E-12	5.95E-07	9.41E-12	1.18E-06	3.65E-11
6000	6.08E-07	2.61E-12	1.38E-06	1.18E-11	1.14E-06	2.20E-11	2.38E-06	8.51E-11
6500	9.49E-07	4.07E-12	2.34E-06	2.12E-11	1.85E-06	3.57E-11	4.23E-06	1.59E-10
7000	1.46E-06	6.15E-12	3.92E-06	3.65E-11	2.97E-06	6.92E-11	7.11E-06	3.35E-10
7500	1.85E-06	7.84E-12	5.33E-06	5.33E-11	4.02E-06	1.07E-10	1.01E-05	5.50E-10
8000	2.43E-06	9.95E-12	7.49E-06	7.71E-11	5.43E-06	1.41E-10	1.48E-05	9.16E-10
Cases:	Baseline, No		amed = 25, No		asteep = 25, No		Both = 25, No	

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 20. SFPOF Comparison for Degradation Parameter amed and asteep

Time	PCD	PCD	PCD	PCD
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
500	4.66E-06	4.46E-06	4.97E-06	4.76E-06
1000	1.03E-05	9.47E-06	1.14E-05	1.06E-05
1500	2.28E-05	2.05E-05	2.60E-05	2.34E-05
2000	5.03E-05	4.45E-05	5.74E-05	5.09E-05
2500	1.07E-04	9.40E-05	1.21E-04	1.07E-04
3000	2.10E-04	1.85E-04	2.35E-04	2.08E-04
3500	3.80E-04	3.37E-04	4.21E-04	3.72E-04
4000	6.33E-04	5.65E-04	6.94E-04	6.18E-04
4500	9.84E-04	8.83E-04	1.07E-03	9.56E-04
5000	1.44E-03	1.30E-03	1.54E-03	1.39E-03
5500	1.97E-03	1.80E-03	2.10E-03	1.91E-03
6000	2.55E-03	2.34E-03	2.71E-03	2.48E-03
6500	3.16E-03	2.92E-03	3.35E-03	3.08E-03
7000	3.83E-03	3.55E-03	4.05E-03	3.73E-03
7500	4.52E-03	4.21E-03	4.76E-03	4.41E-03
8000	5.22E-03	4.87E-03	5.50E-03	5.10E-03
Cases:	Baseline	25 amed, No	25 asteep, No	25 both, No

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 21. PCD Comparison for Degradation Parameter amed and asteep

4.3.4. Replacement Time Impact

To demonstrate the impact of sensor replacement time given the same amount of degradation (both amed and asteep with 25% degradation), several replacement times are considered. The results shown in Tables 22 and 23 are summarized with the following findings:

1. Shorter replacement time will reduce the risk, e.g., replace sensor set every 5 years. When the sensor replacement time increased, due to the timing of replacement, the impact to the risk could be somewhat random. For example, the risk at 8000 hours with 20 years replacement = 3.47E-6 is actually smaller than the risk at 8000 hours with 15 years replacement = 5.14E-6. This can be attributed to the "timing" for comparison.
2. As for PCD, the impact of replacement time was not as obvious as for risk. The PCD at various hours seem to have the same detection percentage.

Time	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After
0	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00
500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2500	2.90E-12	4.00E-15	1.96E-12	4.00E-15	2.90E-12	4.00E-15	2.90E-12	4.00E-15	2.90E-12	4.00E-15	2.90E-12	4.00E-15
3000	3.30E-10	4.00E-15	2.26E-10	4.00E-15	3.30E-10	4.00E-15	3.30E-10	4.00E-15	3.30E-10	4.00E-15	3.30E-10	4.00E-15
3500	6.85E-09	9.19E-14	3.55E-09	1.20E-14	4.11E-09	1.20E-14	6.85E-09	9.19E-14	6.85E-09	9.19E-14	6.85E-09	9.19E-14
4000	5.15E-08	8.55E-13	2.43E-08	1.42E-13	2.56E-08	1.50E-13	5.15E-08	8.55E-13	5.15E-08	8.55E-13	5.15E-08	8.55E-13
4500	1.92E-07	3.98E-12	8.67E-08	3.74E-13	8.81E-08	6.66E-13	1.92E-07	8.47E-13	1.92E-07	3.98E-12	1.92E-07	3.98E-12
5000	5.50E-07	1.29E-11	1.95E-07	9.89E-13	2.51E-07	2.23E-12	2.69E-07	1.35E-12	5.50E-07	1.29E-11	5.50E-07	1.29E-11
5500	1.18E-06	3.65E-11	3.82E-07	2.36E-12	5.50E-07	5.87E-12	4.23E-07	2.57E-12	1.18E-06	3.65E-11	1.18E-06	3.65E-11
6000	2.38E-06	8.51E-11	7.62E-07	3.20E-12	1.15E-06	4.84E-12	7.86E-07	5.61E-12	2.38E-06	1.05E-11	2.38E-06	8.51E-11
6500	4.23E-06	1.59E-10	1.04E-06	5.30E-12	1.23E-06	6.27E-12	1.36E-06	1.17E-11	1.66E-06	8.46E-12	4.23E-06	1.59E-10
7000	7.11E-06	3.35E-10	1.65E-06	9.85E-12	1.73E-06	1.04E-11	2.37E-06	2.40E-11	1.90E-06	1.13E-11	7.11E-06	3.35E-10
7500	1.01E-05	5.50E-10	2.31E-06	9.68E-12	2.35E-06	1.70E-11	3.48E-06	4.19E-11	2.44E-06	1.73E-11	1.01E-05	4.58E-11
8000	1.48E-05	9.16E-10	2.65E-06	1.30E-11	3.46E-06	2.92E-11	5.14E-06	7.19E-11	3.47E-06	2.89E-11	4.79E-06	2.40E-11
Cases	Both = 25, No		Both = 25, 5		Both = 25, 10		Both = 25, 15		Both = 25, 20		Both = 25, 25	

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 22. SFPOF Comparison for Different Sensor Replacement Time

Time	PCD	PCD	PCD	PCD	PCD	PCD
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
500	4.76E-06	4.76E-06	4.76E-06	4.76E-06	4.76E-06	4.76E-06
1000	1.06E-05	1.06E-05	1.06E-05	1.06E-05	1.06E-05	1.06E-05
1500	2.34E-05	2.28E-05	2.34E-05	2.34E-05	2.34E-05	2.34E-05
2000	5.09E-05	5.04E-05	5.09E-05	5.09E-05	5.09E-05	5.09E-05
2500	1.07E-04	1.07E-04	1.07E-04	1.07E-04	1.07E-04	1.07E-04
3000	2.08E-04	2.11E-04	2.12E-04	2.08E-04	2.08E-04	2.08E-04
3500	3.72E-04	3.78E-04	3.79E-04	3.72E-04	3.72E-04	3.72E-04
4000	6.18E-04	6.27E-04	6.27E-04	6.18E-04	6.18E-04	6.18E-04
4500	9.56E-04	9.90E-04	9.70E-04	1.01E-03	9.56E-04	9.56E-04
5000	1.39E-03	1.43E-03	1.41E-03	1.44E-03	1.39E-03	1.39E-03
5500	1.91E-03	1.95E-03	1.93E-03	1.95E-03	1.91E-03	1.91E-03
6000	2.48E-03	2.57E-03	2.61E-03	2.51E-03	2.69E-03	2.48E-03
6500	3.08E-03	3.14E-03	3.16E-03	3.11E-03	3.18E-03	3.08E-03
7000	3.73E-03	3.79E-03	3.79E-03	3.77E-03	3.79E-03	3.73E-03
7500	4.41E-03	4.57E-03	4.46E-03	4.45E-03	4.46E-03	4.88E-03
8000	5.10E-03	5.19E-03	5.15E-03	5.14E-03	5.14E-03	5.27E-03
Cases	25 both, No	25 both, 5	25 both, 10	25 both, 15	25 both, 20	25 both, 25

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 23. PCD Comparison for Degradation Parameter amed and asteep

To demonstrate the impact of frequent replacement of sensor set, several cases with high level of degradation limits are considered. The results show that by using a strategy of frequent sensor set replacement, it will greatly improve the risk results due to degradation. In other words, with frequent replacement, the impact of degradation can be alleviated. This additional study increases the degradation limit to a higher level and the impact is still reasonably small even when the degradation limit has been increased to 75% for both amed and asteep.

Time	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After
0	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00
500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2500	1.80E-12	4.00E-15	1.96E-12	4.00E-15	2.25E-12	4.00E-15	2.50E-12	4.00E-15
3000	1.80E-10	4.00E-15	2.26E-10	4.00E-15	2.81E-10	4.00E-15	3.40E-10	4.00E-15
3500	3.21E-09	9.99E-15	3.55E-09	1.20E-14	3.86E-09	1.60E-14	4.17E-09	2.40E-14
4000	2.16E-08	8.59E-14	2.43E-08	1.42E-13	2.71E-08	2.30E-13	3.06E-08	3.64E-13
4500	7.03E-08	3.02E-13	8.67E-08	3.74E-13	1.08E-07	4.72E-13	1.32E-07	5.86E-13
5000	1.80E-07	7.65E-13	1.95E-07	9.89E-13	2.14E-07	1.31E-12	2.30E-07	1.72E-12
5500	3.38E-07	1.47E-12	3.82E-07	2.36E-12	4.30E-07	3.79E-12	4.80E-07	5.97E-12
6000	6.08E-07	2.61E-12	7.62E-07	3.20E-12	9.42E-07	4.00E-12	1.16E-06	4.95E-12
6500	9.49E-07	4.07E-12	1.04E-06	5.30E-12	1.16E-06	6.98E-12	1.24E-06	9.15E-12
7000	1.46E-06	6.15E-12	1.65E-06	9.85E-12	1.84E-06	1.58E-11	2.06E-06	2.49E-11
7500	1.85E-06	7.84E-12	2.31E-06	9.68E-12	2.86E-06	1.21E-11	3.55E-06	1.50E-11
8000	2.43E-06	9.95E-12	2.65E-06	1.30E-11	2.89E-06	1.72E-11	3.19E-06	2.25E-11
Cases:	Baseline, No		Both = 25, 5		Both = 50, 5		Both = 75, 5	

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 24. SFPOF Comparison for Different High Level Degradation Cases

As for PCD, the impact of the strategy of frequent sensor set replacement is similar to that for the risk. Because of this strategy, the PCD at various hours seem to have the same detection percentage for various degradation cases.

Time	PCD	PCD	PCD	PCD
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
500	4.66E-06	4.76E-06	4.86E-06	4.97E-06
1000	1.03E-05	1.06E-05	1.09E-05	1.12E-05
1500	2.28E-05	2.28E-05	2.28E-05	2.28E-05
2000	5.03E-05	5.04E-05	5.05E-05	5.07E-05
2500	1.07E-04	1.07E-04	1.06E-04	1.07E-04
3000	2.10E-04	2.11E-04	2.11E-04	2.12E-04
3500	3.80E-04	3.78E-04	3.77E-04	3.75E-04
4000	6.33E-04	6.27E-04	6.22E-04	6.16E-04
4500	9.84E-04	9.90E-04	9.96E-04	1.00E-03
5000	1.44E-03	1.43E-03	1.42E-03	1.41E-03
5500	1.97E-03	1.95E-03	1.93E-03	1.91E-03
6000	2.55E-03	2.57E-03	2.59E-03	2.62E-03
6500	3.16E-03	3.14E-03	3.13E-03	3.11E-03
7000	3.83E-03	3.79E-03	3.75E-03	3.72E-03
7500	4.52E-03	4.57E-03	4.62E-03	4.66E-03
8000	5.22E-03	5.19E-03	5.17E-03	5.14E-03
Cases:	Baseline, No	25 both, 5	50 both, 5	75 both, 5

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 25. PCD Comparison for Different High Level Degradation Cases

To further study the impact of replacement schedule, two additional replacement strategies (10 and 15 years) are considered and solved for comparison. As shown, the risk increases when using the replacement schedule of every 10 years instead of every 5 years (see Table 26). A similar result is observed for the 15 year replacement schedule, i.e., a longer replacement schedule will increase the risk accordingly (see Table 27).

Time	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After
0	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00
500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2500	1.80E-12	4.00E-15	2.90E-12	4.00E-15	4.45E-12	4.00E-15	6.25E-12	4.00E-15
3000	1.80E-10	4.00E-15	3.30E-10	4.00E-15	5.62E-10	4.00E-15	9.02E-10	4.00E-15
3500	3.21E-09	9.99E-15	4.11E-09	1.20E-14	5.10E-09	2.60E-14	6.16E-09	3.80E-14
4000	2.16E-08	8.59E-14	2.56E-08	1.50E-13	2.98E-08	2.68E-13	3.47E-08	4.06E-13
4500	7.03E-08	3.02E-13	8.81E-08	6.66E-13	1.11E-07	1.40E-12	1.37E-07	2.83E-12
5000	1.80E-07	7.65E-13	2.51E-07	2.23E-12	3.54E-07	5.99E-12	4.83E-07	1.50E-11
5500	3.38E-07	1.47E-12	5.50E-07	5.87E-12	8.68E-07	2.30E-11	1.29E-06	7.05E-11
6000	6.08E-07	2.61E-12	1.15E-06	4.84E-12	1.96E-06	8.57E-12	3.27E-06	1.44E-11
6500	9.49E-07	4.07E-12	1.23E-06	6.27E-12	1.54E-06	9.48E-12	1.88E-06	1.40E-11
7000	1.46E-06	6.15E-12	1.73E-06	1.04E-11	2.03E-06	1.73E-11	2.35E-06	2.82E-11
7500	1.85E-06	7.84E-12	2.35E-06	1.70E-11	2.94E-06	3.57E-11	3.69E-06	7.20E-11
8000	2.43E-06	9.95E-12	3.46E-06	2.92E-11	4.79E-06	7.89E-11	6.54E-06	2.30E-10
Cases:	Baseline, No		Both = 25, 10		Both = 50, 10		Both = 75, 10	

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 26. SFPOF Comparison for Different High Level Degradation Cases with Different Replacement Schedules

Time	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After	SFPOF Before	SFPOF After
0	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00	4.00E-15	0.00E+00
500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
1500	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2000	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15	4.00E-15
2500	1.80E-12	4.00E-15	2.90E-12	4.00E-15	4.45E-12	4.00E-15	6.25E-12	4.00E-15
3000	1.80E-10	4.00E-15	3.30E-10	4.00E-15	5.62E-10	3.40E-14	9.02E-10	6.60E-14
3500	3.21E-09	9.99E-15	6.85E-09	9.19E-14	1.28E-08	8.29E-13	2.22E-08	3.01E-12
4000	2.16E-08	8.59E-14	5.15E-08	8.55E-13	1.05E-07	9.59E-12	1.98E-07	3.87E-11
4500	7.03E-08	3.02E-13	1.92E-07	8.47E-13	4.34E-07	3.00E-12	8.60E-07	5.22E-12
5000	1.80E-07	7.65E-13	2.69E-07	1.35E-12	3.66E-07	3.39E-12	4.75E-07	4.46E-12
5500	3.38E-07	1.47E-12	4.23E-07	2.57E-12	4.94E-07	6.50E-12	5.77E-07	8.99E-12
6000	6.08E-07	2.61E-12	7.86E-07	5.61E-12	9.62E-07	1.73E-11	1.18E-06	2.90E-11
6500	9.49E-07	4.07E-12	1.36E-06	1.17E-11	1.84E-06	4.55E-11	2.51E-06	1.06E-10
7000	1.46E-06	6.15E-12	2.37E-06	2.40E-11	3.61E-06	1.22E-10	5.32E-06	3.43E-10
7500	1.85E-06	7.84E-12	3.48E-06	4.19E-11	5.87E-06	2.84E-10	9.44E-06	9.02E-10
8000	2.43E-06	9.95E-12	5.14E-06	7.19E-11	9.50E-06	6.02E-10	1.70E-05	2.33E-09
Cases:	Baseline, No		Both = 25, 15		Both = 50, 15		Both = 75, 15	

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 27. SFPOF Comparison for Different High Level Degradation Cases with Different Replacement Schedules

As for PCD, the impact of frequent replacement of sensor set strategy is much smaller than the risk impact. The PCD results for both replacement schedules of 10 years and 15 years remain pretty close to the results using the replacement schedule of 5 years as shown in Tables 28 and 29. Actually, when increasing the replacement schedule (10 or 15 years), the PCD decreases more than the replacement schedule of 5 years.

Time	PCD	PCD	PCD	PCD
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
500	4.66E-06	4.76E-06	4.86E-06	4.97E-06
1000	1.03E-05	1.06E-05	1.09E-05	1.12E-05
1500	2.28E-05	2.34E-05	2.40E-05	2.48E-05
2000	5.03E-05	5.09E-05	5.19E-05	5.31E-05
2500	1.07E-04	1.07E-04	1.07E-04	1.09E-04
3000	2.10E-04	2.12E-04	2.13E-04	2.14E-04
3500	3.80E-04	3.79E-04	3.77E-04	3.76E-04
4000	6.33E-04	6.27E-04	6.22E-04	6.16E-04
4500	9.84E-04	9.70E-04	9.58E-04	9.47E-04
5000	1.44E-03	1.41E-03	1.39E-03	1.37E-03
5500	1.97E-03	1.93E-03	1.90E-03	1.88E-03
6000	2.55E-03	2.61E-03	2.67E-03	2.73E-03
6500	3.16E-03	3.16E-03	3.15E-03	3.14E-03
7000	3.83E-03	3.79E-03	3.76E-03	3.72E-03
7500	4.52E-03	4.46E-03	4.41E-03	4.36E-03
8000	5.22E-03	5.15E-03	5.09E-03	5.03E-03
Cases:	Baseline, No	25 both, 10	50 both, 10	75 both, 10

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 28. PCD Comparison for Different High Level Degradation Cases with Different Replacement Schedules

Time	PCD	PCD	PCD	PCD
0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
500	4.66E-06	4.76E-06	4.86E-06	4.97E-06
1000	1.03E-05	1.06E-05	1.09E-05	1.12E-05
1500	2.28E-05	2.34E-05	2.40E-05	2.48E-05
2000	5.03E-05	5.09E-05	5.19E-05	5.31E-05
2500	1.07E-04	1.07E-04	1.07E-04	1.09E-04
3000	2.10E-04	2.08E-04	2.07E-04	2.08E-04
3500	3.80E-04	3.72E-04	3.69E-04	3.68E-04
4000	6.33E-04	6.18E-04	6.09E-04	6.05E-04
4500	9.84E-04	1.01E-03	1.03E-03	1.05E-03
5000	1.44E-03	1.44E-03	1.43E-03	1.43E-03
5500	1.97E-03	1.95E-03	1.93E-03	1.91E-03
6000	2.55E-03	2.51E-03	2.48E-03	2.45E-03
6500	3.16E-03	3.11E-03	3.07E-03	3.03E-03
7000	3.83E-03	3.77E-03	3.72E-03	3.68E-03
7500	4.52E-03	4.45E-03	4.39E-03	4.34E-03
8000	5.22E-03	5.14E-03	5.07E-03	5.03E-03
Cases:	Baseline, No	25 both, 15	50 both, 15	75 both, 15

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 29. PCD Comparison for Different High Level Degradation Cases with Different Replacement Schedules

Based on the above findings, Tables 30 and 31 are developed based on the risk (SFPOF) and PCD data at the 8000 FH of various replacement schedules. The ratio of SFPOF based on the 5 years replacement schedule seems to increase gradually when the degradation limit increases as shown in Table 30. For the 75% degradation limit, the ratio gets up to 1.311, i.e., the SFPOF at 8000 FH is found equal to the baseline (no degradation and no replacement) SFPOF at 8000 FH times the ratio of 1.311.

When using the replacement schedule of 10 years, the ratio for 25% degradation limit case becomes 1.423 and which is already larger than the 75% degradation with 5 years replacement schedule. The ratio gets up to 2.689 for the case with 75% degradation limit.

The same ratio gets up to 7 when considering a 15 years replacement schedule. Based on the above discussion, it can be concluded that frequent sensor replacement should be considered as the most critical element to avoid the impact of degradation especially when the degradation limit can be controlled within 25% limit. It should be used to set the requirement for the degradation limit.

Replacement Schedule	SFPOF(25 both) / SFPOF (baseline)	SFPOF(50 both) / SFPOF (baseline)	SFPOF(75 both) / SFPOF (baseline)
5 years	1.087	1.189	1.311
10 years	1.423	1.969	2.689
15 years	2.111	3.905	7.004

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 30. SFPOF Ratio for Different High Level Degradation Cases with Different Replacement Schedules at 8000 Flight Hours

As for PCD, the impact of frequent replacement of sensor set strategy again can be found much smaller than the risk. As shown in Table 31, the ratio of PCD based on the 5 years replacement schedule seems to increase very slightly when the degradation limit increases. For the 75% degradation limit, the ratio gets up to 1.015 only, i.e., the PCD at 8000 FH can be found equal to baseline (no degradation and no replacement) PCD at 8000 FH divided by the ratio of 1.015.

When using the replacement schedule of 10 years, the ratio for 25% degradation limit case remained a small number of 1.013 and which is pretty close to the 75% degradation with 5 years replacement schedule. The ratio only gets up to 1.037 for the case with 75% degradation limit and the same ratio only gets up to 1.038 when considering a 15 years replacement schedule. Based on the above discussion, it can be concluded that frequent replacement of sensor sets will not impact the PCD value greatly. The decision for setting the degradation limit should be based on the risk results.

Replacement Schedule	PCD (baseline) / PCD(25 both)	PCD (baseline) / PCD(50 both)	PCD (baseline) / PCD(75 both)
5 years	1.005	1.010	1.015
10 years	1.013	1.026	1.037
15 years	1.016	1.028	1.038

*Cases: degradation parameters (amed, asteep, or both) and its percentage, sensor set replacement time

Table 31. PCD Comparison for Different High Level Degradation Cases with Different Replacement Schedules at 8000 Flight Hours

4.3.5. Summary of Bulkhead Example Results

From the results, the following key findings are summarized:

1. The impact of replacement schedule plays an important role for the allowable degradation limit.
    a. When the replacement schedule is shorter, i.e., every 5 years, the degradation limit can be increased up to 25% and the impact on risk or PCD will be minimized to 8.7% and 0.5%, respectively.

b. When the replacement schedule is longer, i.e., every 10 years, based on the same degradation limit, the impact on risk or PCD will be increased to 42.3% and 1.3%, respectively.

c. When the replacement schedule is shorter, i.e., every 5 years, the degradation limit can be increased up to 50% and the impact on risk or PCD will be increased to 18.9% and 1%, respectively. The impact here is actually smaller than the case with 10 years replacement schedule and 25% degradation limit.

d. Based on the above data, the decision for setting the degradation limit should be based on the risk results because it is more sensitive to the degradation limit and replacement schedule.

2. The cost impact study should be followed to check if the cost will be increased due to degradation limit and replacement schedule. Discussed in the next Section.

    a. Higher degradation will cause the risk and the total number of repairs to be increased. The cost will be increased accordingly.

    b. Frequent replacement of sensor set will reduce the risk and total number of repairs but it will increase the cost for replacement.

To accommodate the new parameters of degradation limit and the time to replace to the sensor sets, the RBDMS code has been upgraded to perform the calculation with consideration of these two new input data by adding additional input data for the degradation limits (amed and asteep) and replacement schedule (no. of years).

4.4. Integration with CBA Analysis

The CBA analysis can be used to assess the impact of the SHM degradation model with consideration of sensor replacement schedule. A sensitivity study will be performed by considering various POD degradation limits and replacement schedules. Based on sensitivity study results, define requirements for the following key parameters:

- SHM POD capability degradation limit
- Sensor reliability
- Sensor replacement schedule.

To perform CBA analysis, the following assumptions are considered for the baseline SHM design:

1. For the baseline SHM design, consider a SHM design with two critical sensors:
    a. When one of the critical sensors fails, correlation scatter will increase. It will influence the detection capability's asteep factor. Assuming the impact of one critical sensor failure won't influence the results greatly and can be absorbed by the asteep degradation assumption.
    b. When both of them failed, detection capability will be impacted greatly and immediate repair may be needed. Under this condition, before the replacement of the sensor set, the chance of two critical sensors failing must be small enough to avoid the unexpected repair action. A 1.E-7 risk for both

sensors to fail may be imposed to avoid this failure mode. Based on the assumed risk, the reliability of the sensors can be calculated.
   c. When other non-critical sensors fail, the detection capability should not be influenced.
2. Degradation model: This one depends on the choice of damage Index (DI) or algorithm scheme. The following two options will be considered:
   a. Option 1: Assume the DI of a SHM algorithm will degrade linearly and continuously through the design life (60 years), a selected percentage of degradation (α) in amed will be considered. In other words, the amed at the end of 60 years equals to [amed * (1 + α%)]. Also amed at the end of t years equals to [amed * (1 + α%*(t/60))].
   b. Option 2: Assume correlation quality between DI and crack length will degrade linearly and continuously through the design life (60 years) – the percentage degradation in asteep will be considered. The same computation strategy for amed can be applied to asteep parameter, i.e., asteep at the end of t years equals to [asteep * (1 + α%*(t/60))].
3. Sensor repair/replacement strategy decision:
   a. Assume a very small probability of failure (allowable risk of 1.E-7) for two critical sensors to fail. Replace the whole set at the selected number of PDM only. Based on this setup, the reliability of the critical sensor can be defined.
   b. If repair option considered, the cost impact due to repair must be evaluated and compared with the "no repair" option. For this baseline model, only "no repair" option to the sensor will be considered.

4.4.1. DTA 181 Results Summary

Based on the above baseline model definition, the first demonstration example selected for the sensitivity analysis is DTA 181. The following sensitivity conditions are considered for DTA 181:

1. Degradation limit
   a. 0% for both amed and asteep
   b. 25% for both amed and asteep
   c. 50% for both amed and asteep
   d. 75% for both amed and asteep
2. Replacement schedule
   a. No replacement
   b. Every PDM
   c. Every two PDM
   d. Every three PDM

Table 32 and Figure 9 provide a comparison of the POD parameters (amed and asteep) given the above degradation limits. The corresponding crack sizes at PODs equal to 50% and 90% are also calculated.

	amed	asteep	a50	a90
UHF Sensor POD	0.0346	0.3479	0.0346	0.0541
Both 25%	0.0433	0.4348	0.0433	0.0755
Both 50%	0.0519	0.5218	0.0519	0.1013
Both 75%	0.0606	0.6088	0.0606	0.1322

Table 32. Various Degradation Limits Comparison

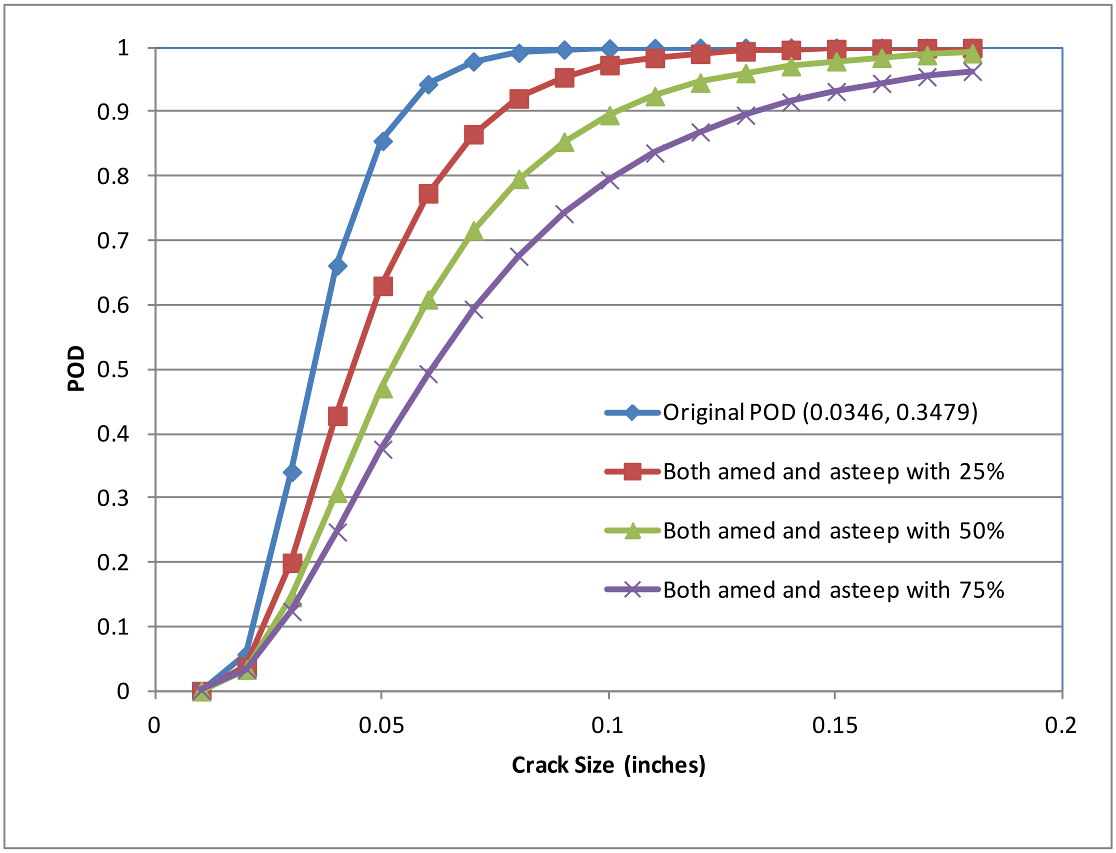

Figure 9. Various Degradation Limits Comparison

For the replacement cost, the following formulas are used:

1. Cost of replacement for every PDM case
   a. 10 times over the life
   b. (10 replacements) *2 * [(5 hours)*($80/hr) + ($750)] = $23,000
2. Cost of replacement for every two PDM
   a. 5 times over the life
   b. (5 replacements) *2* [(5 hours)*($80/hr) + ($750)] = $11,500
3. Cost of replacement for every three PDM
   a. 3.333 times over the life
   b. (3.333 replacements) *2* [(5 hours)*($80/hr) + ($750)] = $7,666.6

Based on the above input, the sensitivity results are summarized in Table 33. The following key observations are found:

1. Degradation Limit increase
    a. SFPOF increase and PCD decrease (see Tables 34 and 35)
    b. SFPOF can be reduced by using smaller degradation limit.
    c. Cost increase as degradation limit increase (see Tables 36 and 37)
2. Replacement PDM no. increase, i.e., replace every 3 PDM
    a. SFPOF increase and PCD decrease (see Tables 34 and 35)
    b. SFPOF can be reduced by using frequent replacement of sensor sets
    c. Larger replacement PDM no. will reduce cost but the cost of failure could be an impact. For this case, the cost of replacement dominates the overall cost, i.e., no replacement will have the minimum cost design (see Tables 36 and 37).

Replacement PDM	Degradation Limit %	Insp LCC	Rep LCC	FA LCC	Fail LCC	Max SFPOF	Sum SFPOF	Sum PCD	sum of cost w/o replacement cost	sum of cost with replacement cost
0	0	123	17,013	1,442	2,786	1.34E-08	8.28E-07	7.01E-01	21,363	21363.5
0	5	123	17,500	1,442	2,971	1.51E-08	8.89E-07	6.97E-01	22,036	22036.0
0	10	123	17,966	1,442	3,157	1.58E-08	9.43E-07	6.94E-01	22,687	22686.9
0	15	123	18,399	1,442	3,342	1.65E-08	1.01E-06	6.91E-01	23,305	23305.5
0	20	123	18,762	1,442	3,476	1.72E-08	1.04E-06	6.89E-01	23,802	23802.4
0	25	123	19,126	1,442	3,614	1.73E-08	1.07E-06	6.86E-01	24,305	24304.7
0	50	123	20,362	1,442	4,274	2.13E-08	1.26E-06	6.77E-01	26,201	26200.8
0	75	123	21,138	1,442	4,903	2.41E-08	1.43E-06	6.71E-01	27,606	27605.6
1	5	123	17,035	1,442	2,791	1.36E-08	8.29E-07	7.00E-01	21,390	44389.8
1	10	123	17,054	1,442	2,815	1.26E-08	8.36E-07	7.00E-01	21,433	44433.5
1	15	123	17,113	1,442	2,837	1.37E-08	8.41E-07	7.00E-01	21,514	44514.1
1	20	123	17,141	1,442	2,839	1.27E-08	8.42E-07	7.00E-01	21,544	44544.3
1	25	123	17,140	1,442	2,852	1.42E-08	8.46E-07	7.00E-01	21,556	44556.2
1	50	123	17,287	1,442	2,945	1.55E-08	8.88E-07	7.00E-01	21,796	44795.8
1	75	123	17,399	1,442	2,999	1.60E-08	9.05E-07	6.99E-01	21,962	44962.2
2	5	123	17,084	1,442	2,835	1.35E-08	8.41E-07	7.00E-01	21,483	32983.3
2	10	123	17,186	1,442	2,869	1.41E-08	8.51E-07	7.00E-01	21,620	33120.0
2	15	123	17,235	1,442	2,881	1.44E-08	8.58E-07	7.00E-01	21,681	33180.8
2	20	123	17,318	1,442	2,900	1.50E-08	8.63E-07	7.00E-01	21,783	33282.9
2	25	123	17,393	1,442	2,947	1.53E-08	8.80E-07	6.99E-01	21,905	33405.4
2	50	123	17,769	1,442	3,104	1.59E-08	9.34E-07	6.98E-01	22,437	33937.3
2	75	123	18,075	1,442	3,243	1.68E-08	9.79E-07	6.97E-01	22,882	34382.1
3	5	123	17,157	1,442	2,846	1.29E-08	8.41E-07	7.00E-01	21,568	29234.1
3	10	123	17,282	1,442	2,903	1.52E-08	8.57E-07	7.00E-01	21,749	29416.0
3	15	123	17,428	1,442	2,933	1.56E-08	8.73E-07	6.99E-01	21,925	29591.9
3	20	123	17,553	1,442	2,979	1.60E-08	8.89E-07	6.99E-01	22,097	29763.3
3	25	123	17,675	1,442	3,034	1.64E-08	9.08E-07	6.98E-01	22,273	29939.8
3	50	123	18,263	1,442	3,250	1.71E-08	9.82E-07	6.96E-01	23,077	30744.0
3	75	123	18,736	1,442	3,433	1.82E-08	1.03E-06	6.94E-01	23,734	31400.4

Table 33. DTA 181 Sensitivity Results

Replacement Schedule	SFPOF (25 both) / SFPOF (baseline)	SFPOF (50 both) / SFPOF (baseline)	SFPOF (75 both) / SFPOF (baseline)
6 years	1.022	1.072	1.093
12 years	1.063	1.128	1.182
18 years	1.097	1.186	1.244
No Replacement	1.292	1.522	1.727

Table 34. DTA 181 Sensitivity Results – SFPOF Comparison

Replacement Schedule	PCD (25 both) / PCD (baseline)	PCD (50 both) / PCD (baseline)	PCD (75 both) / PCD (baseline)
6 years	0.999	0.999	0.997
12 years	0.997	0.996	0.994
18 years	0.996	0.993	0.990
No Replacement	0.979	0.966	0.957

Table 35. DTA 181 Sensitivity Results – PCD Comparison

Replacement Schedule	Cost (25 both) / Cost (baseline)	Cost (50 both) / Cost (baseline)	Cost (75 both) / Cost (baseline)
6 years	1.009	1.020	1.028
12 years	1.025	1.050	1.071
18 years	1.043	1.080	1.111
No Replacement	1.138	1.226	1.292

Table 36. DTA 181 Sensitivity Results – Cost Comparison without Replacement Cost

Replacement Schedule	Cost (25 both) / Cost (baseline)	Cost (50 both) / Cost (baseline)	Cost (75 both) / Cost (baseline)
6 years	2.086	2.097	2.105
12 years	1.564	1.589	1.609
18 years	1.401	1.439	1.470
No Replacement	1.138	1.226	1.292

Table 37. DTA 181 Sensitivity Results – Cost Comparison with Replacement Cost

Based on this demonstration example's results, the overall cost can be reduced by increasing the baseline replacement schedule from the current "replacement every two PDM" to "no replacement or replacement every 10 PDM" (i.e., increase the reliability requirement or increase the redundancy for the sensor design). The results show that "no replacement" or "replacement every 10 PDM" is the most cost-effective optimal design.

When considering the degradation limit, the SFPOF can be reduced by considering frequent replacement of sensor sets as shown in Table 35. However, the cost of failure saving is found much smaller than the cost of frequent replacement of sensor sets. Therefore, when considering the degradation limit, the "no replacement" option will still be the most optimal design. When the saving of frequent replacement (i.e., reducing SFPOF or cost of failure) exceeds the cost of replacement, different optimal design can be found.

To further study if the cost of replacement could be exceeded by the cost of failure saving, additional CPs will be run. In addition, since various SHM strategies are considered for each CP, the impact of this degradation limit and replacement schedule to the selected SHM strategies will also be calculated and studied. Under this condition, additional DTA 181 runs have been performed.

For DTA 181, the most optimal SHM strategies results for various degradation limits (e.g., 25 means both amed and asteep will have 25% degradation) are summarized in Table 38 and its corresponding costs data are summarized in Table 39.

Degradation	0	25	50	75
1	shm_HL_200	shm_HL_200	shm_HL_200	shm_HL_200
2	shm_ML_200	shm_ML_200	shm_ML_200	shm_ML_200
3	shm_HL_300	shm_HL_300	shm_HL_300	shm_HL_300
4	shm_IL_200	shm_IL_200	shm_IL_200	shm_IL_200
5	shm_HI_300	shm_ML_300	shm_ML_300	shm_ML_300

Table 38. DTA 181 Sensitivity Results – SHM Strategy without Replacement of Sensor

Degradation	0	25	50	75
1	24800.7	27741.9	29638.0	31042.9
2	25426.4	28267.0	30211.0	31426.2
3	25606.1	28523.1	30375.4	31573.7
4	26353.7	29116.6	30926.6	32061.7
5	26477.8	29409.6	31153.2	32332.0

Table 39. DTA 181 Sensitivity Results – Cost Comparison without Replacement Cost of Sensor

As shown, the identified optimal SHM strategies for this DTA are not changed due to degradation limit and its cost increases when the degradation limit gets increases. The same kind of observation can also be applied when considering different time to replace the sensor sets. Based on the most optimal SHM strategy (smallest cost design), Tables 40 and 41 summarize the LCC with and without replacement cost, respectively.

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	24801	27742	29638	31043
Replacement in 2 PDM	24801	25343	25875	26319
Replacement in 3 PDM	24801	25710	26515	27171

Table 40. DTA 181 Sensitivity Results – Cost Comparison without Replacement Cost of Sensor

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	24801	27742	29638	31043
Replacement in 2 PDM	36301	36843	37375	37819
Replacement in 3 PDM	32467	33377	34181	34838

Table 41. DTA 181 Sensitivity Results – Cost Comparison with Replacement Cost of Sensor

For comparison purpose, the above two LCC tables' cost data have been divided by the baseline LCC cost of 24801 and Tables 42 and 43 created.

As shown in Table 42, without replacement cost, the overall cost increases when using higher degradation limit and more time between replacements (no replacement case will have the highest cost). With consideration of replacement cost, the condition gets reversed and the case without replacement will have the smallest cost. In other words, given a selected degradation limit, the best strategy is not to replace the sensor sets in the design lifetime. Under this condition, depending on the SHM design, the sensor reliability requirement must be quite high in order for the SHM system to last for a lifetime without two critical sensor failures.

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	1.000	1.119	1.195	1.252
Replacement in 2 PDM	1.000	1.022	1.043	1.061
Replacement in 3 PDM	1.000	1.037	1.069	1.096

Table 42. DTA 181 Sensitivity Results – Cost Comparison without Replacement Cost of Sensor

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	1.000	1.119	1.195	1.252
Replacement in 2 PDM	1.464	1.486	1.507	1.525
Replacement in 3 PDM	1.309	1.346	1.378	1.405

Table 43. DTA 181 Sensitivity Results – Cost Comparison with Replacement Cost of Sensor

4.4.2. DTA 179 Results Summary

For DTA 179, without replacement of sensor sets, the most optimal SHM strategies results for various degradation limits (both amed and asteep) are summarized in the following Table 44. Its corresponding cost data are summarized in Table 45.

Degradation	0	25	50	75
1	shm_ML_600	shm_ML_600	shm_ML_300	shm_ML_300
2	shm_ML_300	shm_ML_300	shm_IL_300	shm_IL_300
3	shm_IL_300	shm_IL_300	shm_ML_200	shm_ML_200
4	shm_ML_900	shm_ML_200	shm_IL_200	shm_LL_300
5	shm_IL_600	shm_IL_600	shm_LL_300	shm_IL_200

Table 44. DTA 179 Sensitivity Results – SHM Strategy without Replacement of Sensor

Degradation	0	25	50	75
1	53130.32255	58563.26568	62934.9666	65351.88995
2	53351.10736	59050.59114	64454.82626	66595.62159
3	54938.73713	60823.93354	64879.16625	67576.59251
4	55906.85468	60977.07554	65733.77018	68164.94319
5	56608.92028	61407.88926	66222.30794	68286.4334

Table 45. DTA 179 Sensitivity Results – Cost Comparison without Replacement Cost of Sensor

As shown in Table 44, the identified optimal SHM strategies will be influenced by the degradation limit, i.e., when the degradation limit increased, the optimal SHM strategy changed. The cost also increased when the degradation limit increased. The same kind of observation can also be applied to the replacement of sensor sets.

Based on the optimal SHM strategy (smallest cost design), Tables 46 and 47 summarize the cost for with and without replacement cost, respectively.

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	53130	58563	62935	65352
Replacement in 2 PDM	NA	NA	NA	NA
Replacement in 3 PDM	53130	54925	56385	57703

Table 46. DTA 179 Sensitivity Results – Cost Comparison without Replacement Cost of Sensor

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	53130	58563	62935	65352
Replacement in 2 PDM	NA	NA	NA	NA
Replacement in 3 PDM	60797	62592	64052	65370

Table 47. DTA 179 Sensitivity Results – Cost Comparison with Replacement Cost of Sensor

For comparison purpose, the above two tables' cost data will be used and divided by the baseline cost of 53130 to create Tables 48 and 49.

As shown in Table 48, without the replacement cost, the overall cost increased with higher degradation limit and more time between replacements (i.e., no replacement case will have the highest cost). With consideration of the replacement cost, the condition will be reversed and the case without replacement will have the smallest cost unless a very large

degradation limit is considered. At the 75% degradation limit, the overall cost for no replacement and replacement in 3 PDM are almost the same. In other words, the cost impact due to degradation can be offset by the cost of replacement. Under this condition, the sensor reliability requirement could be based on the requirement to replace the sensor sets every three PDM (or 18 years) which should be much better than the requirement for no replacement of sensor sets.

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	1.000	1.102	1.185	1.230
Replacement in 2 PDM	NA	NA	NA	NA
Replacement in 3 PDM	1.000	1.034	1.061	1.086

Table 48. DTA 179 Sensitivity Results – Cost Comparison without Replacement Cost of Sensor

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	1.000	1.102	1.185	1.230
Replacement in 2 PDM	NA	NA	NA	NA
Replacement in 3 PDM	1.144	1.178	1.206	1.230

Table 49. DTA 179 Sensitivity Results – Cost Comparison with Replacement Cost of Sensor

Previously, for the replacement cost, the total number of replacements has been calculated based on math and without consideration of actual replacement of sensors. For the replacement in every three PDM case, the replacement cost was calculated based on 3.333 replacements, which is in fact not a realistic number. For this case, it should consider 3 replacements in a lifetime. Therefore, with the above findings, the following replacement cost formulae have been revised:

1. Cost of replacement for every PDM case
    a. 9 times over the life
    b. (9 replacements) *2 * [(5 hours)*($80/hr) + ($750)] = $20700
2. Cost of replacement for every two PDM
    a. 4 times over the life
    b. (4 replacements) *2* [(5 hours)*($80/hr) + ($750)] = $9200
3. Cost of replacement for every three PDM
    a. 3 times over the life

b. (3 replacements) *2* [(5 hours)*($80/hr) + ($750)] = $6900

Based on the updated cost of replacement, the above Table 49 has been revised and shown in Table 50. As shown, the total LCC for the degradation limit of 75% case, the replacement in 3 PDM case has a smaller LCC than the case without any replacements. For the degradation limit of 50% case, the LCC for both “no replacement” and “replacement in 3 PDM” are very close.

Replacement Schedule	LCC for Degra 0%	LCC for Degra 25%	LCC for Degra 50%	LCC for Degra 75%
No Replacement	1.000	1.102	1.185	1.230
Replacement in 2 PDM	NA	NA	NA	NA
Replacement in 3 PDM	1.130	1.164	1.191	1.216

Table 50. DTA 179 Sensitivity Results – Cost Comparison with Replacement Cost of Sensor

4.4.3. Results Summary

Based on the above 2 DTA analysis results, the following key observations are summarized:

1. For most cases, when SHM design is applied, the calculated single flight probability of failure (SFPOF) should be much smaller than 1.E-7. Under this condition, the cost of failure reduction due to replacement of sensor set should be a smaller number. For both DTA 181 and 179, the cost of failure was found with very small number and LCC was found at the range of 25,000 (DTA 181) to 65,000 (DTA 179). Therefore,
    a. Frequent replacement of sensors impact to the SFPOF won’t translate into a big cost saving.
    b. However, frequent replacement’s impact to the PCD should have some impacts to the repair cost. For DTA 179, the cost of repair impact plays a major role instead of cost of failure as shown in Table 51. Note that the same observation can also be seen in DTA 181 as shown in Table 52 but the cost reduction is less than the cost of replacement.

Degradation 75% and the replacement strategy	Insp LCC	Rep LCC	FA LCC	Fail LCC	LCC W/O Repl Cost	LCC With Repl Cost
No replacement	2360	56818	6149	24	65352	65352
Replace every 3 PDM	2360	49190	6149	4	57703	64603

Table 51. DTA 179 Cost Items Comparison

Degradation 75% and the replacement strategy	Insp LCC	Rep LCC	FA LCC	Fail LCC	LCC W/O Repl Cost	LCC With Repl Cost
No replacement	3560	21138	1442	4903	31043	31043
Replace every 3 PDM	3560	18736	1442	3433	27171	34071

Table 52. DTA 181 Cost Items Comparison

2. The impact of replacement schedule plays an important role for the LCC
   a. For DTA 181, the replacement cost was found much larger than its benefit to the risk and crack found. Therefore, no replacement of sensor sets is the optimal design.
   b. For DTA 179, at the high degradation limit of 75% case, replacement of the sensor set did have a benefit larger than the replacement cost itself. In other words, the optimal design for DTA 179 is to replacement the sensor set every 3 PDMs given a degradation limit of 75%.
   c. As defined earlier, the baseline SHM design considered is a SHM design with two critical sensors. When both of them failed, detection capability will be impacted greatly and immediate repair may be needed. Under this condition, before the replacement of the sensor set, the chance of two critical sensors failing must be small enough to avoid the unexpected repair action. A 1.E-7 risk for both sensors to fail may be imposed to avoid this failure mode. Based on the assumed risk, the reliability of the sensor can be calculated. Based on this assumption, the reliability requirement for DTA 181 and DTA 179 are calculated as follow:
      i. DTA 181- no replacement necessary so no failure allowed in 60 years for two critical sensors to fail. Given the probability of two sensors failure must be less than or equal to 1.E-7, i.e., probability of one sensor failure in 60 years = 3.1623E-4. Based on this probability, the corresponding failure rate can be calculated as 6.0175E-10.
      ii. DTA 179 – assuming it will be replaced every 3 PDMs given 75% degradation limit, the failure requirement for each critical sensor becomes: Given the probability of two sensors failure must be less than or equal to 1.E-7, i.e., probability of one sensor failure in 18 years = 3.1623E-4. Based on this probability, the corresponding failure rate can be calculated as 2.006E-9.
      iii. To reduce the sensor reliability requirement, the redundancy of the system could be considered. By increasing the critical sensors from 2 to 3, the above two cases' failure rate requirement could be reduced:
         1. For DTA 181, the failure rate requirement becomes 8.852E-9.
         2. For DTA 179, the failure rate requirement becomes 2.951E-8.

4.5. Next Steps

Based on the study results, the degradation limit and replacement of sensor set play an important role for the SHM design. From the quantitative risk and cost results, it is possible to determine appropriate requirements for these two factors. Without the cost data, the degradation limit seems to have a major impact on the overall risk results so it is important to reduce the degradation limit. However, with consideration of LCC, the

degradation limit's impact becomes less important compared to the time to replace the sensor set. In most cases, the cost of replacement becomes the major LCC item and no replacement of sensor becomes the optimal design choice. Therefore, to identify the optimal design, it is important to produce the quantitative risk and cost data by performing a sensitivity analysis.

Based on the above findings, several important next steps have been developed in order to set the design requirements for degradation limit and replacement schedule:

1. Need to extend the analysis from the component level to the system level. Examine all the components that have been chosen to use SHM design. Run the CBA analyses for the following case to see if these locations could be influenced by either the degradation limit or the replacement schedule.
    a. 0% degradation limit and no replacement of sensors.
    b. 0% degradation and replacement of sensors in every three PDM. This case will have the same SFPOF and PCD results but the LCC will have to include the cost of replacement. No additional calculation needed for this case.
    c. 75% degradation limit and no replacement of sensors – to check the impact of degradation limit.
    d. 75% degradation limit and sensors replacement in every three PDM – to check the impact of replacement of sensors and compare cost impact.
2. Based on the above results, combine the LCCs of all components and calculate the overall system LCCs for the above four cases. Based on the comparison results, determine the sensitivity of the LCC to the sensor degradation limit and replacement schedule. If degradation limit is the most important factor, an additional case with smaller degradation limit should be run for sensitivity purpose. If the degradation limit is not as important as the replacement schedule, i.e., "no replacement of the sensor" could be the most optimal design. Under this condition, no additional cases need to be run. The selected SHM design for the overall system will be used to determine the allowable degradation limit and the optimal replacement schedule, i.e., sensor reliability requirement.

5. Risk Analysis Progress

5.1. Status as of August 2011 Progress Report

The previous progress report discusses the use of the updated version of RBDMS to obtain estimates of SFPOF and the PCD at future scheduled inspections. The software was used to perform a component-level analysis for a 16 CP subset of the F-15 C/D wing structural system. The methods for determining the Baseline maintenance plan for each location were described, and the various possible strategies for each CP were shown. At that time engineering judgment was used to determine the optimal strategy for each CP.

Several significant changes have taken place regarding the risk analysis since the submission of the previous progress report. For example,

- Utilizing 44 CPs instead of the previous 16 CP subset
- Engineering judgment is no longer required for determination of the optimal strategies for each CP, this step has been automated
- The mechanism for running the many strategies of the risk analysis has been automated
    - This is crucial due to the large set of CPs under consideration
- The "Risk-Based" strategy was renamed to the "Threshold" strategy to reduce confusion
    - All strategies are related to risk, only the Threshold strategy uses the risk threshold to determine the inspection times for the CP
- A more complete collection of strategies is considered for each CP (see Section 0 for more information)
    - In addition to the Baseline and Threshold strategies, a complete set of constant interval NDE strategies are considered (e.g. every 200 FH, every 600 FH, etc.)
    - For the SHM strategies, additional inspection intervals and an additional detection capability / false alarm rate are considered

5.2. Automating the Risk Analysis with ModelCenter®

ModelCenter®, a multi-disciplinary design optimization tool created by Phoenix Integration, is utilized to manage the many different RBDMS runs that must be completed for each CP in this analysis. The goal is to generate all of the required output files with filenames that correspond to the CPs and the various strategies. Here we describe the method at a high level.

A screenshot of the ModelCenter® program is shown below in Figure 10. In the figure we see several important components.

- Component tree on the left containing
    - Input variables specific to a single CP
    - The various "modules" being utilized by the model
- Model window on the right containing several modules
    - Loop
    - Script_RBDMS_Input
    - RBMDS
    - Script_RBMDS_Output

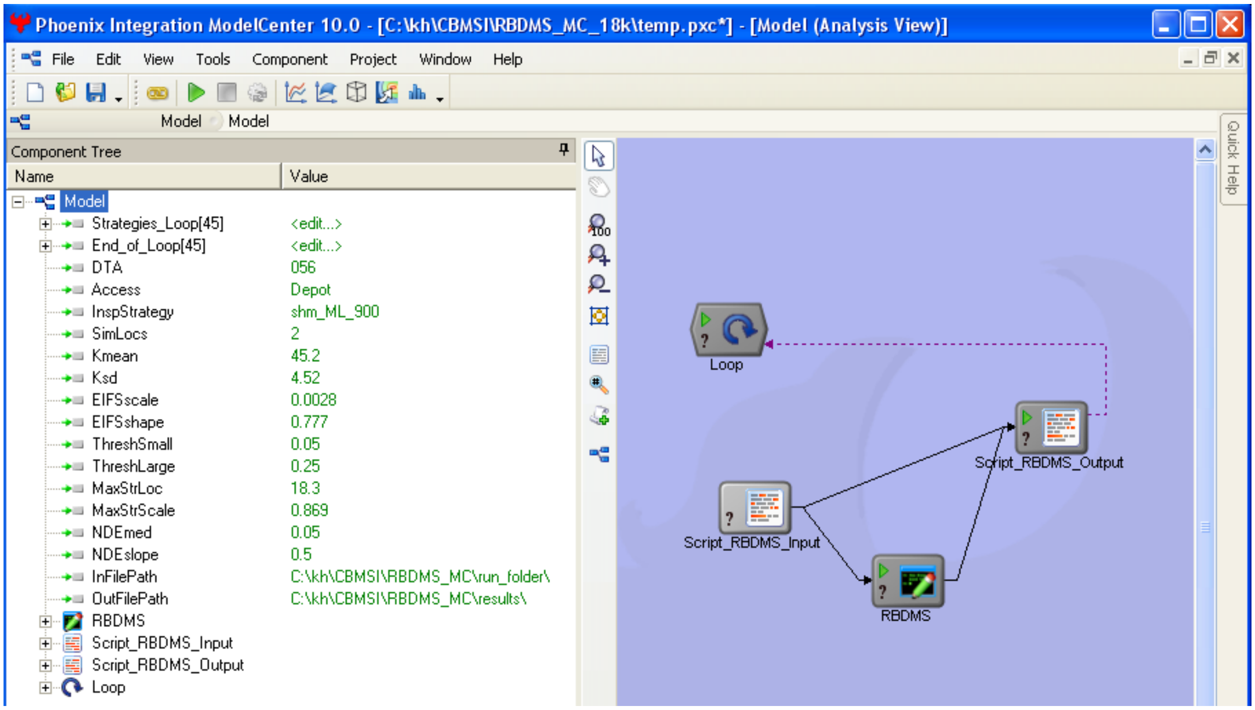

Figure 10. ModelCenter® Screenshot

The familiar RBDMS input variables are listed in the component tree along with a few additional variables specific to this approach: Strategies_Loop, InFilePath, and OutFilePath. Strategies_Loop is a vector of strings containing the list of strategies the user wishes to run for this CP. The naming convention is the same as that used in earlier sections of this report. InFilePath is a local path to the location of the RBDMS input files which are to be modified during each iteration of the loop. Finally, OutFilePath is a path to the location in which the user wishes for the RBDMS output files to be saved.

The loop module controls the operation of the model. It is merely a “For Each” loop which sequentially runs the other three modules once for each component of the vector Strategies_Loop. The following occurs once for each strategy:

- Script_RBMDS_Input Module
  - Scripting code (written in VBA script) examines the name of the current strategy
  - Generates the RBDMS input files appropriate to that strategy (with corresponding inspection times, POD curves, etc.)
- RBDMS module
  - Executes RBDMS.exe (which resides in the folder indicated by InFilePath)
  - Reads the results into ModelCenter
- Script_RBDMS_Output module
  - Exports the results to a file in the folder indicated in OutFilePath
  - Names the output file according to the current CP and strategy

When this operation is complete, a folder containing all results for a single CP has been generated. The CBA utilizes these results.

5.3. Assessment of Risk Analysis Results

It was noted in the previous progress report that the Single Flight Probability of Failure and Probability of Crack Detected results of the risk analysis appear to be artificially high. In this section we look at the results and assess their severity and realism.

The Baseline configuration of this analysis is our attempt to realistically assess the current maintenance plan for the 44 F-15 C/D wing CPs under consideration. A summary table of the risk results for the Baseline configuration is shown in Table 53. Recall, RBDMS only calculates the SFPOF at the scheduled inspection times. The SFPOF is a snapshot of the risk at that time. The table shows the SFPOF before inspections, hence it is a measure of the SFPOF of the flight that occurs just prior to that scheduled inspection. Some observations on the results:

- The Baseline strategy is acceptable for only 8 of 44 CPs
- For 26 CPs (over half), the risk is above the 10^{-7} threshold in 100% of the calculations
- Median PCD is over 10% for 19 CPs and over 20% for 8 CPs
    - PCD is reported *for each similar location*, hence this is a measure of the percentage chance of finding a crack in a typical inspection of a single structural detail

For many of the CPs in our model, the risk predictions are high. If the results are to be believed, we should expect repeated repairs of these parts in service as well as regular failure of the structural system. According to discussions with the Boeing F-15 program, this is clearly not the case in the fleet.

Another way of investigating the level of severity in the assumptions is to examine the initial state by instructing RBDMS to conduct an inspection at time zero. We can then observe the risk of the first flight with and without performing the inspection and subsequent repair. Table 54 presents the SFPOF before and after time zero inspection and the percentage reduction in risk. The percentage reduction can be somewhat misleading due to the low numbers involved, but the conclusion is clear: the risk at time zero is such that performing an inspection at time zero significantly increases the calculated safety of the aircraft. We do not intend to argue that the F-15 fleet should schedule an inspection after assembly of a new aircraft; we merely present this to highlight the fact that the results do not match intuition.

The risk analysis consists of several components for which conservatism in their derivation would result in inflated risk estimates. Two of these which have been identified by the team are as follows.

- Equivalent Initial Flaw Size (EIFS)
    - For both the initial state and for repairs
- Similar Locations
    - Number of “equivalent” locations on each CP and the likelihood of *at least one* failure among these locations

Each of these topics is examined in the following subsections. At this time we note that it is outside the scope of this project to spend a significant amount of time and resources investigating the conservatism of the existing ASIP data. The goal of this project is to define

CP	Access	Max SFPOF Before Insp	# Insp	# Insp > 10-7	% Insp > 10-7	Median PCD (approx)
054B	Field	1.21E-05	4	4	100%	2.05%
054C	Field	4.07E-03	3	3	100%	2.96%
055	Field	2.59E-03	17	3	18%	0.05%
057B	Field	2.62E-03	1	1	100%	0.05%
063B	Field	9.69E-04	1	1	100%	0.37%
112B	Field	6.05E-03	2	2	100%	1.41%
114	Field	8.40E-01	5	5	100%	20.70%
116	Field	9.22E-01	2	2	100%	19.49%
130B	Field	1.20E-01	34	34	100%	1.08%
139	Field	1.00E+00	7	7	100%	8.08%
140	Field	9.99E-01	8	8	100%	11.01%
166B	Field	1.91E-12	12	0	0%	0.01%
180	Field	4.40E-06	2	1	50%	24.93%
184	Field	3.08E-05	42	1	2%	4.69%
187	Field	9.87E-04	42	2	5%	1.15%
188	Field	1.08E-03	5	4	80%	13.79%
191	Field	3.17E-01	5	5	100%	3.17%
194	Field	3.46E-07	9	1	11%	0.92%
056	Depot	1.58E-03	1	1	100%	0.05%
059B	Depot	1.00E+00	1	1	100%	14.76%
097	Depot	2.44E-15	5	0	0%	100.00%
115	Depot	5.00E-01	10	10	100%	7.16%
124B	Depot	6.00E-13	10	0	0%	0.05%
126B	Depot	4.91E-02	10	10	100%	3.97%
131	Depot	1.00E+00	10	10	100%	39.13%
133A	Depot	9.62E-01	10	10	100%	5.81%
134B	Depot	1.68E-04	10	10	100%	27.29%
135B	Depot	8.11E-01	2	1	50%	4.26%
137B	Depot	3.13E-01	7	7	100%	13.40%
138B	Depot	1.21E-03	10	10	100%	57.66%
141	Depot	9.97E-01	10	10	100%	11.94%
143	Depot	1.01E-04	10	9	90%	21.95%
144	Depot	1.33E-02	10	10	100%	10.92%
145	Depot	3.55E-01	2	2	100%	23.45%
179	Depot	5.83E-04	5	5	100%	4.29%
181	Depot	9.84E-01	1	1	100%	26.37%
182	Depot	4.23E-09	3	0	0%	5.29%
183	Depot	4.16E-04	5	1	20%	3.33%
192	Depot	1.20E-09	3	0	0%	8.99%
195	Depot	1.35E-11	2	0	0%	13.08%
196	Depot	2.90E-01	1	1	100%	11.43%
201	Depot	8.99E-10	2	0	0%	11.79%
202	Depot	1.26E-07	7	1	14%	7.40%
203	Depot	2.48E-11	10	0	0%	5.45%

Table 53. Summary of Risk Analysis Results for Baseline Configuration for 44 CPs

CP	SFPOF Before Insp	SFPOF After Insp	Reduction
054B	8.66E-15	1.33E-15	84.62%
054C	4.00E-14	1.33E-15	96.67%
055	7.99E-15	7.99E-15	0.00%
057B	7.11E-15	7.11E-15	0.00%
063B	7.11E-15	7.11E-15	0.00%
112B	1.41E-12	1.08E-13	92.36%
114	2.83E-10	2.84E-12	99.00%
116	7.42E-12	2.93E-12	60.54%
139	1.33E-09	4.25E-10	68.00%
140	7.20E-08	5.22E-10	99.28%
166B	4.44E-16	4.44E-16	0.00%
180	2.20E-10	1.35E-10	38.76%
184	7.92E-11	3.41E-11	56.90%
187	2.09E-09	1.61E-11	99.23%
188	1.53E-13	1.22E-13	20.30%
191	7.40E-10	5.27E-12	99.29%
194	8.30E-14	2.69E-14	67.64%
056	4.05E-12	7.11E-15	99.82%
059B	1.64E-14	1.64E-14	0.00%
097	4.44E-16	4.44E-16	0.00%
115	7.09E-08	5.43E-10	99.23%
124B	2.67E-15	2.67E-15	0.00%
126B	3.11E-09	1.00E-10	96.78%
134B	1.56E-10	1.75E-12	98.88%
135B	6.22E-15	6.22E-15	0.00%
137B	2.67E-14	1.78E-15	93.34%
138B	6.98E-10	3.71E-10	46.82%
141	6.60E-07	6.76E-08	89.77%
143	4.44E-16	4.44E-16	0.00%
144	3.24E-10	3.32E-11	89.76%
179	1.55E-12	3.41E-13	77.97%
181	5.13E-10	1.79E-10	65.13%
182	7.11E-15	7.11E-15	0.00%
183	1.73E-14	1.73E-14	0.00%
192	2.67E-15	2.67E-15	0.00%
195	1.02E-14	1.02E-14	0.00%
196	1.33E-15	1.33E-15	0.00%
201	7.11E-15	7.11E-15	0.00%
202	4.00E-15	4.00E-15	0.00%
203	1.33E-15	4.44E-16	66.66%

Table 54. Time Zero Inspection Results

the CBM+SI process and to demonstrate its use. However, because this demonstration of the process requires these data as inputs, some investigation is required in order to make realistic recommendations regarding the amount of work that may be in store for programs which may choose to adopt our CBM+SI approach.

5.3.1. Equivalent Initial Flaw Size

The EIFS distributions utilized in this analysis were provided by the F-15 program. There is an EIFS for titanium structure and an EIFS for aluminum structure. Both are of the Weibull distribution family. Most of the CPs (41 of 44) are aluminum structure. The two EIFS distributions are shown below in Figure 11. It is easily seen that the aluminum EIFS is far more severe than the titanium EIFS as there is much more weight in the right tail of the distribution.

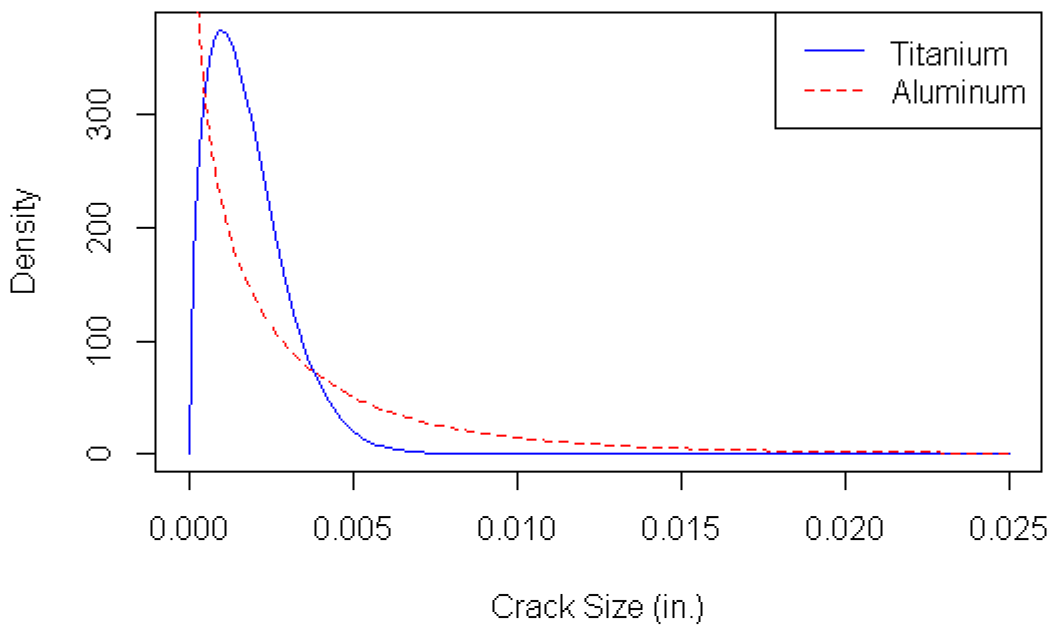

Figure 11. Titanium and Aluminum EIFS Distribution Density Plots

Typical initial flaw sizes for the deterministic analyses for the CPs in question are 0.01" and 0.05", depending on whether the CP is safety of flight critical or durability critical. For the titanium EIFS, the probabilities of an initial crack exceeding 0.01" and 0.05" are 6×10^{-6} and 1×10^{-62}, respectively. For aluminum, these probabilities are 7×10^{-2} and 8×10^{-5}, respectively. Note the striking difference between these and also the fact that for aluminum the probability of having a crack greater than 0.05" at time zero is *higher than the 10^{-7} risk threshold*. This has a significant impact on results and the EIFS distribution for aluminum is most likely too conservative to yield realistic results.

5.3.2. Similar Locations

Many CPs have a large number of *similar locations*. These represent distinct locations on the aircraft for which, at present in the analysis, the assumption is made that the risk posed by each is identical. For example, CP 187 has 134 similar locations (67 for each wing). The SFPOF is first calculated for a single location. The method for calculating SFPOF

for all locations assumes these locations are independent and that all locations are equally severe. Thus, the formula for calculating the probability that *at least one* location will fail on a flight is:

$$SFPOF_{sl} = 1 - (1 - SFPOF_1)^{sl}$$

For example, suppose that SFPOF for a single location is 10^{-8}. With 136 similar locations, SFPOF is calculated as follows, raising the risk by two orders of magnitude.

$$SFPOF_{sl} = 1 - (1 - 10^{-8})^{136} = 1.4 \times 10^{-6}$$

If these locations were 100% correlated, the SFPOF would be 10^{-8}. The correlation is likely between 0% and 100%, suggesting the actual SFPOF for these locations lies between these two extremes. The risk for a single location represents the lower bound. Table 55 presents the Maximum SFPOF for both the original risk analyses and the modified analyses which utilize a single location for each CP. The rightmost column indicates the reduction in the peak SFPOF as a percentage.

In addition to the correlation issue, it is not likely that every location presents equal risk. The crack growth analysis is developed with respect to the most critical location at the CP. If these multiple similar locations represent fastener holes, the other locations may be significantly less severe than the principal critical location.

These two facts suggest there may be room for improvement by conducting a system-level risk analysis *within* each CP, as well as *between* the various CPs.

CP	Original Max SFPOF	1 Sim Loc Max SFPOF	Reduction
054B	1.21E-05	2.01E-06	83.3%
054C	4.07E-03	6.79E-04	83.3%
055	2.59E-03	7.19E-05	97.2%
057B	2.62E-03	8.18E-05	96.9%
063B	9.69E-04	3.03E-05	96.9%
112B	6.05E-03	6.89E-05	98.9%
114	8.40E-01	4.48E-02	94.7%
116	9.22E-01	5.41E-02	94.1%
130B	1.20E-01	6.23E-02	48.3%
139	1.00E+00	1.12E-01	88.8%
140	9.99E-01	2.01E-01	79.9%
166B	1.91E-12	9.53E-13	50.0%
180	4.40E-06	1.87E-08	99.6%
184	3.08E-05	6.42E-07	97.9%
187	9.87E-04	7.37E-06	99.3%
188	1.08E-03	5.42E-05	95.0%
191	3.17E-01	6.18E-02	80.5%
194	3.46E-07	1.57E-08	95.5%
056	1.58E-03	4.95E-05	96.9%
059B	1.00E+00	1.33E-01	86.7%
097	2.44E-15	1.23E-15	49.5%
115	5.00E-01	7.20E-03	98.6%
124B	6.00E-13	5.00E-14	91.7%
126B	4.91E-02	1.26E-03	97.4%
131	1.00E+00	4.37E-01	56.3%
133A	9.62E-01	5.33E-02	94.5%
134B	1.68E-04	2.10E-05	87.5%
135B	8.11E-01	5.78E-02	92.9%
137B	3.13E-01	4.59E-02	85.3%
138B	1.21E-03	3.03E-04	75.0%
141	9.97E-01	6.20E-02	93.8%
143	1.01E-04	5.06E-05	50.0%
144	1.33E-02	6.68E-03	49.8%
145	3.55E-01	8.10E-03	97.7%
179	5.83E-04	2.47E-06	99.6%
181	9.84E-01	2.27E-01	77.0%
182	4.23E-09	1.32E-10	96.9%
183	4.16E-04	5.34E-06	98.7%
192	1.20E-09	9.99E-11	91.7%
195	1.35E-11	2.93E-13	97.8%
196	2.90E-01	5.56E-02	80.8%
201	8.99E-10	2.81E-11	96.9%
202	1.26E-07	6.98E-09	94.4%
203	2.48E-11	1.24E-11	50.0%

Table 55. Comparison of Original SFPOF to 1 Similar Location SFPOF

6. Cost Analysis Progress

A user's manual is in-work for the Excel-based cost model. In this report we discuss the major changes which have taken place since the previous progress report, along with two specific sensitivity analyses which have been conducted. The updated strategy for performing the CBA itself is discussed in the example walkthrough of the flowchart in Section 3.

6.1. Changes Since August Progress Report

As of August 2011 the Cost Benefit Analysis (CBA) Tool calculated the Technical Performance Measures (TPMs) correctly and was capable of supporting up to 16 DTAs. Since that time the following major changes have been incorporated:

- Expanded
    - The tool now allows for up to 50 CPs
    - Additional expansion is possible
- Optimized
    - The tool has been optimized to perform its calculations more rapidly
- Reorganized
    - Arrangement and presentation have been updated to make the tool more accessible
- Streamlined
    - A streamlined, more intuitive version of the spreadsheet was created
    - The macros (which are specifically for use with RBDMS) have been removed to allow for the use of other risk analysis software in its place (e.g. PROF)
- Updated
    - Devised a scheme for finding the optimal NDE and optimal SHM strategies for each CP
    - Developed a method for reducing the total number of configurations to analyze
    - These methodological updates were extensively discussed in Section 3.7 and the discussion is not repeated here

6.1.1. Expanded

Previously the CBA could be utilized with any reasonable number of CPs. However, changing the number of CPs in the system was an involved process which required careful modification of numerous cell formulas across several tabs. At this time the CBA has a fixed number of CPs of 50. If there are fewer than 50, the user may simply leave the lower CPs blank and the CBA will calculate the TPMs correctly.

6.1.2. Optimized

The CBA Tool was slow due to the several inefficient calculations. Many of the cells used nested "IF" statements and very often the number of "IF" statements could be factored down along with reducing the complexity of the equations. Also, several calculations which were previously performed across several cells were combined into single cells; this reduces the total number of cells which Excel needs to update at any time, increasing the speed of calculation.

In its previous form the CBA tool contained both Baseline and Modified tabs which were nearly identical. These tabs were both included so that the Modified configuration could be compared to the Baseline configuration. However, only the TPMs of the Baseline configuration are used to compare to the Modified configuration, and the Baseline configuration is fixed across all possible Modified configurations. Performing the great many calculations of the Baseline tab every time Excel performs a calculation was time consuming. Also, each time an update was made to either tab the duplicate update needed to be made to its twin; this was both time consuming and error prone.

For these reasons the Baseline tab was deleted. In the current version of the tool the TPMs for the Baseline configuration are inputs to the model. This facilitates the required comparison of the Modified configuration to the Baseline. To acquire these inputs, the user simply imports the Baseline configuration and subsequently copies the resulting TPMs into the appropriate input cells.

6.1.3. Reorganized

The CBA Tool was difficult to understand for a new user as the information and data on each tab was laid out in such a way that the user could not see much information at one time. All tabs were given a makeover; common information and data were grouped, cells and headers were colored and reformatted to support visual recognition, titles were changed and added inside tabs to support the understanding of the information presented, many comments were inserted, and several tabs were renamed to be more informative. The tabs names were changed as follows:

- Main → Summary (TPMs)
- Modified → CP Calcs
- SHM Costs → SHM Costs Breakdown
- CostBreakdown → Fleet LifeCycle Costs

Below are screen shots showing the before and after transformation of several of the tabs. Note that the pictures are zoomed out somewhat. The intention is to show the overall structure of the tabs and not the details of the contents.

In Figures 12 and 13, before and after screenshots are shown of the Main/Summary tab, respectively. Previously the user had to scroll up and down to see the entire sheet and related information was not generally grouped together. Now the user can see everything at once with a logical grouping.

AVIATR T.O. 3			
Technical Performance Metrics Model			
Yellow Cells = User-Defined Inputs			
Names		**Common Inputs**	
Number of Platforms in Fleet		300	
Flight Hours / Year / Platform		300	
Number of Years Covered		60	
Flight Hours / Flight		1.3	
Total Flight Hours on One Plane		18000	
Customer Discount Rate		2.70%	
Boeing Discount Rate		10.50%	
Cost/Labor Hour for Customer		$ 80.00	
Platform Cost		$ 25,000,000.00	
Inaccessibility penalty (hrs)		500	
Downtime penalty (hrs)		8	
SHM Inspection Time		0.5	
		Baseline	**Modified Approach**
Description			
Nonrecurring Costs			
SDD (System Design and Development)			$0
Initial Production			$0
Production & Deployment			$0
Installation Labor Hours			2.5
Total Nonrecurring Costs for Modified Approach			$0
NPV Nonrecurring - Customer			$0
NPV Nonrecurring - Boeing			$0
Recurring Costs			
Fleet O&S Costs / Year for Modified Approach			$0
Total Recurring Costs for Modified Approach			$0
NPV Recurring for Modified Approach - Customer			$0
NPV Recurring for Modified Approach - Boeing			$0
Number of Inspections for the Fleet		48,300	405,000
Total Expected Inspection Costs		$9,384,000	$9,336,000
NPV Inspect Costs - Customer		$4,365,853	$4,343,521
NPV Inspect Costs - Boeing			
Total Fleet Downtime		117,300	1,012,500
Number of Repairs for Fleet		212,227	210,040
Total Expected Repair Costs		$1,458,045,407	$1,830,983,643
NPV Repair Costs - Customer		$678,347,315	$851,854,704
NPV Repair Costs - Boeing			
Total Fleet Downtime		6,765,696	7,674,803
Predicted Number of Failures for the Fleet		7,385,237	#REF!
Total Expected Failure Cost		$469,701,245,740	$469,684,707,825
NPV Fail Costs - Customer		$218,525,827,436	$218,518,133,265
NPV Fail Costs - Boeing			
Total Equivalent Fleet Downtime		957,245	974,916
Availability or Mission Capable (%)		78.00%	76.84%
Fleet Downtime - Elapsed Downtime		7,840,241	9,662,219
Calendar Hours NMC		34,689,600	36,511,578
Calendar Hours NMC Outside of Target Structure		26,849,359	26,849,359
Equivalent Fleet Size Benefit ($)			-$86,661,825
NPV Equ. Fleet Benefit - Customer			-$40,318,920
NPV Equ. Fleet Benefit - Boeing			
Total Recurring Costs ($/Platform/Year)		$26,176,038	$26,200,649
NPV Recurring - Customer ($/Platform/Year)		$12,178,252	$562,601,668
NPV Recurring - Boeing ($/Platform/Year)		$0	$0
% of NMC Due to Downtime for Target Structure		22.60%	26.46%
Labor Hours		287,173,451	292,475,662
Life Cycle Cost (LCC)		$471,168,675,147	$471,611,689,293
LCC Difference			($443,014,147)
Net Present Value (NPV) - Customer		$219,208,540,604	$219,414,650,410
NPV Difference - Customer			($206,109,807)

Figure 12. Main / Summary Tab, Before Transformation

Cost Analysis Input Parameters	
Platform/Fleet Information	
Platforms in Fleet	300
Flight Hours / Year / Platform	300.0
Service Life (yrs)	60.0
Hours / Flight	1.3
Service Life in Flight Hours	18000.0
Cost Parameters	
Customer Discount Rate	2.70%
Platform Cost	$25,000,000
Cost/Labor Hour for Customer	$80.00
Cost/Labor Hour for OEM	$180
Cost/Labor Hour for SHM Supplier	$200
Miscellaneous Inputs	
Inaccessibility Labor Penalty (hrs)	500.0
Inaccessibility Downtime Penalty (hrs)	8.0
SHM Inspection Time (hrs)	0.5
SHM Installation Labor Hours	5.0
Proportion of Inaccessibility as MMH	0.92
Downtime Multiplier (0 - 1)	0.6

USER INPUT CELLS IN YELLOW

Calculated Fleet Lifecycle Costs		
Inspection Costs	**Baseline**	**Modified**
Number of Inspections for the Fleet	54,900	94,200
Total Expected Inspection Costs	$10,404,000	$17,460,000
Total Expected NPV Inspection Costs	$4,274,666	$7,152,639
Total Expected Downtime - Inspections (hrs)	11,400	12,900
Repair Costs	**Baseline**	**Modified**
Number of Repairs for Fleet	226,825	468,360
Total Expected Repair Costs	$578,974,481	$1,324,819,418
Total Expected NPV Repair Costs	$221,900,048	$581,772,697
Total Expected Downtime - Repairs (hrs)	838,556	851,937
False Alarm Costs	**Baseline**	**Modified**
Number of Unnecessary Repairs for Fleet	-	-
Total Expected Unnecessary Repair Costs	$0	$0
Total Expected NPV Unnecessary Repair Costs	$0	$0
Total Expected Downtime - False Alarms (hrs)	0.00E+00	0.00E+00
Failure Costs	**Baseline**	**Modified**
Predicted Number of Failures for the Fleet	13,690	33,110
Total Expected Failure Cost	$61,816,696,310	$140,893,761,248
Total Expected NPV Failure Costs	$22,045,544,782	$58,744,576,919
Total Expected Downtime - Failures (hrs)	1.66E+07	4.52E+07
SHM Development Thru Deployment - Non-Recurring Costs	**Baseline**	**Modified**
SDD (System Design and Development)	$ -	$0
Initial Production	$ -	$0
Production & Deployment	$ -	$0
Total Non-Recurring Costs	$ -	$0
NPV Non-Recurring	$ -	$0
SHM O&S - Recurring Costs	**Baseline**	**Modified**
Fleet O&S Costs / Year	$ -	$0
Total Recurring Costs	$ -	$0
NPV Recurring Costs	$ -	$0

Technical Performance Measures Lifecycle Costs		
Total Costs (Fleet)	**Baseline**	**Modified**
LCC NPV (not including equivalent fleet size benefit)	$22,271,719,496	$59,333,502,255
LCC Net Present Value of Costs (NPV)	$22,271,719,496	$59,966,078,839
LCC (not including equivalent fleet size benefit)	$62,406,074,791	$142,236,040,666
Life Cycle Cost (LCC)	$62,406,074,791	$143,595,075,744
Recurring Costs (Platform)	**Baseline**	**Modified**
Total Recurring Costs ($/Platform/Year)	$3,467,004	$7,977,504
Total NPV Recurring Costs ($/Platform/Year)	$1,237,318	$3,331,449
Downtime TPMs Comparison	**Baseline**	**Modified**
Availability or Mission Capable (%)	78.00%	**59.88%**
Fleet Downtime - Elapsed Downtime (hrs)	17,452,764.1	46,025,117.6
Calendar Hours NMC	34,689,600.0	63,261,953.5
Calendar Hours NMC Outside of Target Structure	17,236,835.9	17,236,835.9
% of NMC Due to Downtime for Target Structure	50.31%	72.75%
Other	**Baseline**	**Modified**
Equivalent Fleet Size Benefit ($)	$0	-$1,359,035,078
NPV Equivalent Fleet Size Benefit ($)	$0	-$632,576,585
Total Expected Labor Hours	8,824,718	25,119,236
Expected MH/FH	1.63	4.65
TPMs Comparison	**Baseline**	**Modified**
Life Cycle Cost (LCC)	$62,406,074,791	$143,595,075,744
Availability or Mission Capable (%)	78.00%	59.88%
Expected MH/FH	1.6	4.7

Figure 13. Main / Summary Tab, After Transformation

In Figures 14 and 15, before and after screenshots are shown of the Modified/CP Calcs tab, respectively. Previously the columns were not organized in a logical order. These were rearranged to make the tab easier to understand.

For Modified Configuration
Assume linear increase between SFPOFs at each inspection interval
Assume that at inspection, cracks can be detected and repaired.
For a single platform, calculate the expected loss over the entire period in question
Probability of Detection (POD)
Single Flight Probability of Failure (SFPOF)
So the total cost involves the labor and material cost of inspections and repairs.

Names	Common Inputs
Flight Hours / Year / Platform	300
Flight Hours / Flight	1.3
Total Flight Hours on One Plane	18000
Customer Discount Rate	2.70%
Cost/Labor Hour for Customer	$ 80.00
Number of Years Covered	60
Inaccessibility penalty (hrs)	500
Downtime penalty (hrs)	8
DTA items with SHM	0
SHM Inspection Time (hrs)	0.5
SHM Time Per Inspection (hrs)	0

Sum from all zones for one platform		
Total Expected Inspection Costs	$31,120	
Total Expected Repair Costs	$6,103,279	
Total Expected Failure Costs	$1,565,615,693	
Total Expected Inspections	1350.0	
Total Expected Inspection Downtime (Hours)	3375.0	
Total Expected Inspection Labor Hours	3375.0	
Total Expected Repairs	700.1	
Total Expected Repair Downtime (Hours)	25582.7	
Total Expected Repair Labor Hours	25582.7	** Assume 1 Maintainer performing maintenance therefore Downtime = Labor time
Total Expected Failures	#REF!	
Total Expected Failure Downtime (Hours)	945958.7	
Total Expected Failures Labor Hours	945958.7	** Assume 1 Maintainer performing maintenance therefore Downtime = Labor time

dta055	1	Field Item	dta055_base.out	
Descriptions	**Totals**	**Type 1: in-situ**	**Type 2: in-situ w/ penalties**	**Type 3: NDE**	
Labor Hours/Inspection		0	0	2	Only a short period of time is needed to download the sensor readings; access to the bulkhead is only needed for repairs
Material and Additional Costs/Inspection		$ -	$ -	$ -	Tools for inspection
Pr (False Call)		0	0	0	
Hours per False Call		8	508	8	
Expected False Call Cost		$ -	$ -	$ -	
Total Number of Inspections / Plane	**90**	0	0	90	
Cost/Inspection		$ -	$ -	$ 160.00	
Total Cost/Inspection		$ -	$ -	$ 160.00	
Elapsed Downtime (Hours)/Inspection		0	0	2	Assume elapsed downtime is equal to the required labor time
Expected Inspection Downtime (Hours)	**180**	0	0	180	
Expected Inspection Labor Hours	**180**	0	0	180	
In-Flight Failure Cost		$ 50,000.00	Type 1 Value Used	Type 1 Value Used	
Part Replacement Cost		$ 50,000.00	$ 50,000.00	$ 50,000.00	
Number of Holes Inspected		36	Type 1 Value Used	Type 1 Value Used	
Labor Hours, Small Crack Repair		8	508	8	From Jeff McF; hours to repair crack smaller than 0.05"
Labor Hours, Med Crack Repair		60	560	60	From Jeff McF; hours to repair crack between 0.05" & 0.25"
Labor Hours, Large Crack Replacement		160	660	160	From Jeff McF; hours to replace part since crack is greater than 0.25"
Material and Additional Costs/Repair		0	0	0	Materials for repair
Cost for Small Crack Repair		$ 640.00	$ 40,640.00	$ 640.00	
Cost for Med Crack Repair		$ 4,800.00	$ 44,800.00	$ 4,800.00	
Cost for Large Crack Repair		$ 62,800.00	$ 102,800.00	$ 62,800.00	
Expected Downtime (Hours) for Small Repair			66.2		Assume elapsed downtime is equal to the required labor time
Expected Downtime (Hours) for Med Repair			1,798.3		Assume elapsed downtime is equal to the required labor time
Expected Downtime (Hours) for Replacement			1,106.7		Assume elapsed downtime is equal to the required labor time
Total Expected Repair Downtime (Hours)	**2971.1**		**2,971.1**		

Net Present Values here assume that the dollar's value changes at a continuous time, not just every year.

Inspection Flight Hour Time	Inspection Type: 1 = 2 = 3 =	SFPOF (Before Repair)	SFPOF (After Repair)	Small Crack POD for 1 Hole	Med Crack POD for 1 Hole	Large Crack POD for 1 Hole	Downtime (Hrs) Small Crack POD for 1 hole	Downtime (Hrs) Med Crack POD for 1 hole	Downtime (Hrs) Large Crack POD for 1 hole	# of flts between inspections	Change in SFPOF after 1 Flight	Calendar Hrs Platform Down	Expected Inspection Cost Each Interval	Expected Fail Cost Each Interval	Expected Repair Cost for Entire Area (All Spots)	Customer NPV Expected Inspection Cost Each Interval	Customer NPV Expected Fail Cost Each Interval	Customer NPV Expected Repair Cost for Entire Area (All Spots)	POF/# of Failures
0		1.00E-16	1.00E-16																
9600	3	1.00E+00	2.26E-03	1.56E-01	2.22E-01	1.80E-01	1.25E+00	1.33E+01	2.88E+01	7385	1.35E-04	1.40E+05	$ 160.00	############	$ 448,589.66	$ 66.42	#########	$ 186,219.27	3.69E+03
11200	3	1.13E-01	4.28E-05	4.42E-03	3.57E-01	2.62E-03	3.54E-02	2.14E+01	4.19E-01	1231	8.97E-05	2.69E+03	$ 160.00	$ 3,538,058.49	$ 67,656.16	$ 57.62	#########	$ 24,365.41	7.08E+01
13000	3	2.10E-01	6.78E-05	1.22E-02	9.04E-02	6.89E-03	9.78E-02	5.43E+00	1.10E+00	1385	1.52E-04	5.53E+03	$ 160.00	$ 7,280,002.06	$ 31,486.72	$ 49.11	#########	$ 9,664.32	1.46E+02
14600	3	7.21E-02	2.60E-05	1.70E-02	3.75E-02	1.53E-03	1.36E-01	2.25E+00	2.44E-01	1231	5.85E-05	1.69E+03	$ 160.00	$ 2,222,871.86	$ 10,333.79	$ 42.60	#########	$ 2,751.66	4.45E+01
16400	3	2.04E-02	5.88E-06	1.86E-02	6.33E-02	4.80E-04	1.48E-01	3.80E+00	7.69E-02	1385	1.47E-05	5.37E+02	$ 160.00	$ 707,957.08	$ 12,451.95	$ 36.31	#########	$ 2,825.85	1.42E+01
18000	3	3.03E-02	1.17E-05	2.15E-02	6.31E-02	7.15E-04	1.72E-01	3.78E+00	1.14E-01	1231	2.46E-05	7.08E+02	$ 160.00	$ 932,671.49	$ 13,007.11	$ 31.50	#########	$ 2,560.85	1.87E+01
	3						0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00	$ -	$ -	$ -	$ -	$ -	$ -	0.00E+00

Figure 14. Modified/CP Calcs Tab, Before Transformation

Parameters Common to Each CP	
Flight Hours / Year / Platform	300
Hours / Flight	1.3
Service Life in Flight Hours	18000
Customer Discount Rate	2.70%
Cost/Labor Hour for Customer	$80.00
Service Life (yrs)	60
Inaccessibility Labor Penalty (hrs)	500
Inaccessibility Downtime Penalty (hrs)	8
# of Unique CPs with SHM	0
SHM Inspection Time (hrs)	0.5
Platform Cost	$25,000,000
Proportion of Inaccessibility as MMH	0.92

Summary of Inspection Results	
Scheduled Number of Inspections	314.0
Scheduled Number of SHM Inspections	0
Expected Total Inspection Costs	$58,200
Expected Inspection Downtime	43.0
Expected Inspection Labor Hours (MMH)	727.5

Summary of Repair Results	
Expected Number of Repairs	1561.2
Expected Total Repair Costs	$4,416,065
Expected Repair Downtime	2839.8
Expected Repair Labor Hours (MMH)	48309.5

Summary of False Alarm Results	
Expected Number of False Alarms	0.00E+00
Expected Total False Alarm Costs	$0.00
Expected False Alarm Downtime	0.00E+00
Expected False Alarm Labor Hours (MMH)	0.00E+00

Summary of Failure Results	
Expected Number of Failures	1.10E+02
Expected Total Failure Costs	$469,645,870.83
Expected Failure Downtime	1.51E+05
Expected Failure Labor Hours (MMH)	3.47E+04

In this tab, the life cycle costs due to inspection, repair, false alarms and failures is estimated **FOR A SINGLE PLATFORM**.

These cells are hard wired for 50 control points.

Parameters For This CP Only

Variable Description	Value
CP Name	054B
Row # In CP Info Tab	1
Accessibility	Field
Results Shown Below	054B_nde_base.out
Similar Locations (e.g. # of Holes)	6
In-Flight Failure Cost	$11,400
Part Replacement Cost	$5,000
Additional Costs/Inspection	$0
Additional Costs/Repair	$0
Labor Hours, Single Small Crack Repair	8.0
Labor Hours, Single Medium Crack Repair	0.0
Labor Hours, Single Large Crack Part Replacement	80.0
Cost, Single Small Crack Repair	$640
Cost, Single Medium Crack Repair	$0
Cost, Single Large Crack Part Replacement	$11,400

Variable Description	Insp Type 1: SHM	Insp Type 2: SHM with Penalties	Type 3: NDE	Totals
Labor Hours/Inspection	0.000	0.000	3.000	
Pr (False Alarm)	0	0	0	
Cost / Inspection	$0	$0	$240	
Expected Number of False Alarms	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total Number of Inspections / Plane	0.0	0.0	3.0	3.0
Expected Inspection Labor Hours	0.0	0.0	9.0	9.0

Results From Risk Analysis Software

Inspection Flight Hour Time	Inspection Type: 1 = 2 = 3 =	SFPOF (Before Repair)	SFPOF (After Repair)	Small Crack Probability of Crack Detection (PCD) for 1 Hole	Medium Crack Probability of Crack Detection (PCD) for 1 Hole	Large Crack Probability of Crack Detection (PCD) for 1 Hole	A/C Downtime at This Inspection For Reasons Other Than Structures	Inspection Calculations: Expected Inspection Cost	Expected Downtime For Inspection	Repair Calculations: Expected Repair Cost for All Holes	Expected Downtime Due to Repair for all Holes	MMH Due to Repair for All Holes	False Alarm Calculations: Expected False Alarm Cost for All Holes	Expected Downtime for False Alarms for All Holes	Expected MMH for False Alarms for All Holes
0	0	8.66E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00									
4600	3	7.88E-06	4.35E-13	1.51E-02	0.00E+00	1.83E-03	0	$240.00	3.00E+00	$182.58	1.60E+00	1.60E+00	$0.00	0.00E+00	0.00E+00
9200	3	9.95E-06	2.71E-13	1.83E-02	0.00E+00	2.19E-03	57.6	$240.00	0.00E+00	$219.07	2.94E-01	1.93E+00	$0.00	0.00E+00	0.00E+00
13800	3	1.21E-05	3.31E-13	2.16E-02	0.00E+00	2.68E-03	86.4	$240.00	0.00E+00	$265.19	0.00E+00	2.32E+00	$0.00	0.00E+00	0.00E+00
18000	3	7.63E-06	2.06E-13	2.24E-02	0.00E+00	2.84E-03	2592	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00
							0	$0.00	0.00E+00	$0.00	0.00E+00	0.00E+00	$0.00	0.00E+00	0.00E+00

Figure 15. Modified/CP Calcs Tab, After Transformation

Other tabs were updated in similar fashion. They are omitted from this document. The forthcoming user's manual will contain detailed screenshots which will walk the user through the operation of the entire workbook.

6.1.4. Streamlined

The core functionality of the CBA is contained within Excel in the traditional manner. That is, the risk analysis results and the various other inputs are placed into cells and cell formulas are used to obtain the TPM results for a configuration.

In addition to the core functionality, a number of additional support tabs were created specifically to speed up the import of RBDMS results through the use of Visual Basic for Applications (VBA) macros. These macros are inessential to the functioning of the CBA itself.

A version of the CBA has been created in which the macros and the macro support tabs have been removed. This streamlined version contains the following tabs.

- GR&A
    - Ground Rules and Assumptions
    - Informational tab, not referenced elsewhere in the workbook
- Summary (TPMs)
    - The resulting TPMs are located here, along with several inputs to the model
- CP Calcs
    - Calculates the expected costs for inspections, repairs, false alarms and failures
    - Contains inputs throughout including the risk analysis results
- CP Summary
    - Shows the costs from CP Calcs broken down by CP
    - Informational tab, not referenced elsewhere in the workbook
- SHM Cost Breakdown

    - Calculates the non-recurring and recurring SHM costs for the current configuration
- Fleet Lifecycle Costs
    - Primarily performs the discounting of all of the fleet costs over the lifetime
- CP Info
    - Matrix of inputs specific to the CPs
- Flight Intervals
    - Simply a vector of the natural numbers
    - Used by “Fleet Lifecycle Costs” to assist the discounting procedure
- Downtimes by FH
    - Matrix of the hours for which the plane is grounded at each possible inspection time
    - The downtime due to maintenance of the CP Calcs tab is in excess of the numbers here

6.2. Sensitivity of Results to Service Life Assumption

The selected service life for this project is 18,000 FH. At an assumed average usage of 300 FH/yr, this represents 60 years, which is a relatively long period of time. To test the sensitivity of the results to the service life assumption, the analysis was also run at 8,100 and 12,000 FH (both a multiple of 300 so that the service life is an integer number of years).

The Best NDE and Optimal configurations from the 18,000 FH service life were re-analyzed at the shorter service lives and entered in the CBA. For the 8,100 FH service life, the nde_9000 strategies of CPs 097, 192, and 201 are replaced with nde_8100 as there are no required inspections for these locations at this service life. Figure 16 below depicts the total LCC for each configuration in discounted (NPV) dollars, along with the components of these costs. The components are inspection, repair, false alarm and failure costs (or Insp, Rep, FA and Fail). The SHM costs in the figure include both the non-recurring and recurring costs. The LCC is approximately linear in service life between 8,100 and 18,000 FH for both the Best NDE and Optimal configurations. A tabulated version which includes some additional information follows in Table 56.

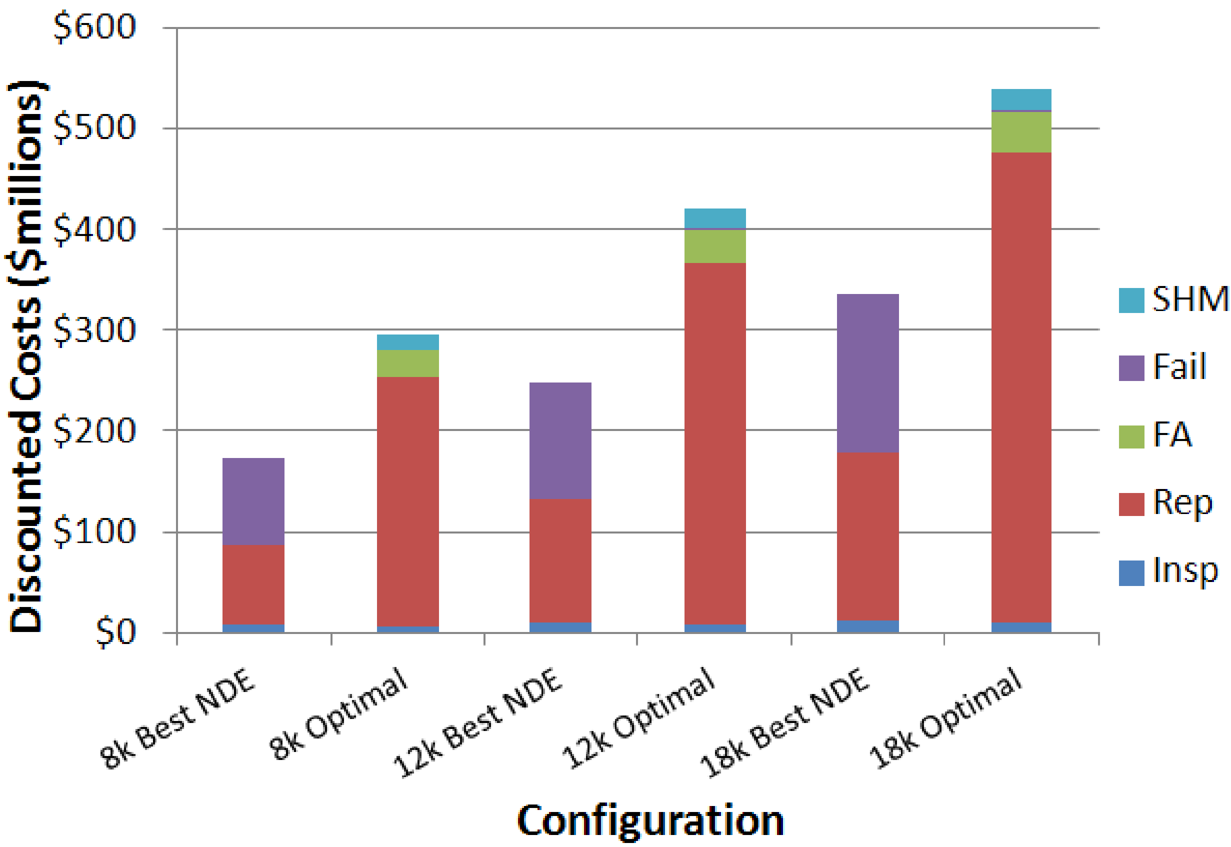

Figure 16. Discounted Cost Component Comparison; 8k, 12k, and 18k FH Service Lives

	8,100 FH Life		12,000 FH Life		18,000 FH Life	
	8k Best NDE	8k Optimal	12k Best NDE	12k Optimal	18k Best NDE	18k Optimal
Insp NPV ($t)	7,560	6,366	9,771	8,203	12,064	10,122
Rep NPV ($t)	78,882	247,820	122,627	359,429	166,361	466,280
FA NPV ($t)	–	25,567	–	32,686	–	39,964
Fail NPV ($t)	86,538	863	115,263	1,193	156,982	1,499
NPV ($t)	172,981	296,608	247,661	420,114	335,406	539,076
LCC ($t)	269,698	454,221	456,008	767,451	810,622	1,239,958
Fleet DT (hr)	157,356	197,197	236,400	302,564	360,289	460,603
# SHM CPs	–	8	–	8	–	8
Total SHM NPV ($t)	–	15,991	–	18,603	–	21,210

Table 56. Cost Components in Thousands of Dollars; 8k, 12k, and 18k FH Service Lives

6.3. Sensitivity of Results to NDE False Alarm Rate

In this analysis we have assumed an NDE false alarm rate of 0%. This is not necessarily true in practice; hence we check the sensitivity of the results to this assumption. The analysis was also run with a false alarm rate of 1%. In Figure 17 and Table 57 below we compare the results of the Best NDE and Optimal configurations using false alarm rates of 0% and 1%. Note that the costs of false alarms in the figure include both NDE and SHM false alarms. The effect of the increase in the false alarm rate to 1% is not trivial. Should this analysis be performed for production every effort should be made to appropriately characterize the NDE false alarm rates.

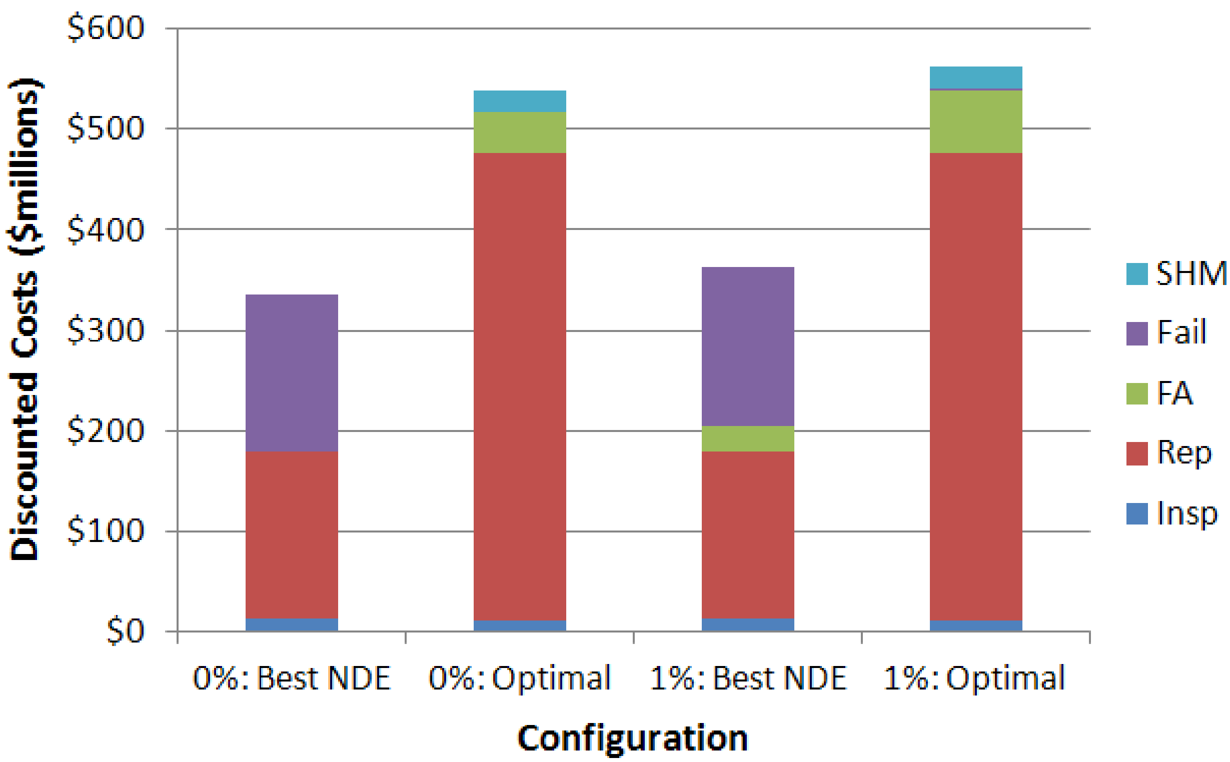

Figure 17. Discounted Cost Component Comparison; NDE Pr(FA) = 0% vs. 1%

	NDE FA rate = 0%			NDE FA rate = 1%		
	Baseline	Best NDE	Optimal	Baseline	Best NDE	Optimal
Insp NPV ($t)	4,275	12,064	10,122	4,275	12,064	10,122
Rep NPV ($t)	221,900	166,361	466,280	221,900	166,361	466,280
FA NPV ($t)	–	–	39,964	5,195	26,462	62,505
Fail NPV ($t)	22,045,545	156,982	1,499	22,045,545	156,982	1,499
NPV ($t)	22,271,719	335,406	539,076	22,276,914	361,868	561,617
LCC ($t)	62,406,075	810,622	1,239,958	62,419,283	867,535	1,288,387
Fleet DT (hr)	17,411,660	360,289	460,603	17,440,736	430,483	530,797
# SHM CPs	–	–	8	–	–	8
Total SHM NPV ($t)	–	–	21,210	–	–	21,210

Table 57. Cost Components in Thousands of Dollars; NDE Pr(FA) = 0% vs. 1%

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Acronyms, Symbols and Abbreviations

CBM+SI	Condition-Based Maintenance plus Structural Integrity
CP	Control Point
DC	Durability Critical Aircraft part(s)
DIR	Directly-Tracked aircraft part
DTA	Damage Tolerance Analysis/Assessment
FSMP	Force Structural Maintenance Plan
FST	Full-Scale Test
IATP	Individual Aircraft Tracking Program
IND	Indirectly-Tracked Aircraft Part
IND(L)	Indirectly-Tracked Aircraft Part linked to a directly-tracked part
INS	In-Service
LCC	Life Cycle Cost
MMH	Maintenance Man Hours
MOQS	Maintenance Operational Query System
NDI	Non-Destructive Inspection
NMC	Non-Mission Capable
%NMC	% Fleet Non-Mission Capable
NPV	NET-Present Value
PROF	Probability of Failure; Air Force code used to determine Risk of a part(s)
POD	Probability of Detection
RBDMS	Risk-Based Design & Maintenance System; Boeing code used to determine Risk of a part(s)
REMIS	Air Force's Reliability and Maintenance Information System
SFPOF	Single Point Probability of Failure
SHM	Structural Health Monitoring
TPM	Technical Performance Measurements
WUC	Work Unit Code